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Estimates of Collision Risk of Harbour Porpoises and Marine Renewable Energy Devices at Sites of High Tidal-Stream Energy

marine scotland

ESTIMATES OF COLLISION RISK OF HARBOUR PORPOISES AND MARINE RENEWABLE ENERGY DEVICES AT SITES OF HIGH TIDAL-STREAM ENERGY

Report prepared for the Scottish Government.

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Executive Summary

Extracting renewable energy from the sea is an attractive alternative to burning fossil fuels. Like any marine industry, obtaining energy from wind, waves or tidal-streams could have impacts on the marine environment (positive or otherwise). One frequently cited area of uncertainty for extracting energy from fast flowing tidal currents is the possibility of large marine vertebrates (including whales, dolphins, porpoises [collectively cetaceans], seals, sharks, turtles, and diving birds) colliding with submerged tidal-turbines – a scenario with parallels to the issues surrounding bird strikes by wind turbines.

Preliminary modelling work has suggested that interactions between tidal turbines and harbour porpoises (Scotland's most abundant cetacean) may be common, assuming porpoises occur in tidal-stream areas at densities similar to other Scottish coastal habitats. However, it remains unclear how true this assumption is, and particularly whether porpoises avoid or are attracted to these areas. The aim of this study, therefore, was to investigate how often porpoises occurred in two areas of immediate interest for tidal-stream development on the west coast of Scotland. These two sites were the tidal narrows of the Sound of Islay (between the islands of Islay and Jura) and the Kyle Rhea (between Skye and the mainland).

Surveys were carried out during the summers of 2009 and 2010 using a variety of standard and specifically adapted techniques. The primary tool was the use of a research boat (the Hebridean Whale and Dolphin Trust's *RV Silurian*) which was used to criss-cross the sites with observers visually scanning for surfacing porpoises. In addition, the vessel towed hydrophones to detect the echolocation calls of submerged animals. While these techniques are used routinely to investigate porpoise occurrence, the strength of the tidal streams meant that at times the water was moving at speeds close to that of the boat itself. This unusual feature, if ignored, could have severely biased the survey results. We therefore corrected the survey path with respect to the flow so that the boat crabbed across the moving water-mass at an equivalent rate to the progress over the bottom. We tested this new method and successfully applied it to both sites and their adjacent waters over a total of 16 days covering 1300 km of sea.

Harbour porpoises were seen and acoustically detected in all of the areas surveyed. Of particular interest for this study were the areas of strongest tidal flow in the Sound of Islay and the Kyle Rhea. Porpoises were seen and acoustically detected in both of these sites. However, rates of sightings and acoustic detections were an order of magnitude lower than surrounding waters. For example, sighting rates in the Kyle Rhea narrows were around 0.01 km^{-1} whereas to the south in the Sound of Sleat they ranged from 0.09 – 0.22 km^{-1}. Acoustic detections showed a similar pattern with 0.2 click events km^{-1} in the narrows and 5.4 km^{-1} in open water immediately to the south.

While confirming that porpoises were not absent from these tidal-energy relevant habitats, the boat surveys demonstrated that porpoises occurred at such low densities in the fast flowing water that that our original plans for shore-based observations to investigate behaviour would be unrewarding within the time limits of the project. We therefore explored other techniques to better understand porpoise

activity. We initially investigated the use of moored acoustic porpoise echolocation click detectors (C-PODs), a standard technique used in many places to monitor porpoise presence. Their use, however, also proved problematic because of the flowing water. This time the water flowing past the fixed recorders produced high levels of noise which obscured the devices' abilities to detect porpoise calls. Deployments out of (but adjacent to) the strong flows were successful and the results were variable, suggesting that precise patterns of porpoise occurrence were site-specific and that many recorders would be needed to properly assess their use of such an area.

Given that the water movement was problematic for porpoise click recorders held stationary in the flow, we also explored the use of the same equipment but allowed it to drift freely in the current as part of location logging drogue systems. These proved highly successful and rapidly revealed patterns of porpoise distribution similar to the more intensive boat-based surveys. That said, because the recorders drifted with the current within which the animals were also moving, interpretation of the results requires care. In addition to mapping porpoise detections, the drifters also revealed spatial patterns in the distribution of the problematic ambient noise and may therefore be useful for determining where similar devices could be moored more successfully.

We also tested a new acoustic array-based method to determine the diving depth of echolocating porpoises. This method could be deployed from a drifting boat in flowing water and was therefore workable in tidal-energy sites where other methods were impractical. The trial revealed that dives were surprisingly shallow for this species despite some of the recordings being made in deep water. This suggests that diving behaviour data collected from other habitats may not be directly applicable to tidal energy sites.

Given these results, what, then, are the implications for likely rates of interaction between porpoises and operating tidal turbines? If we apply the new results to the encounter model used previously to investigate this issue, then the potential interaction rate falls from 13 to around 1.8 to 3.25 porpoise "encounters" per turbine per year. It must, however, be emphasized that this number is not a collision rate, but simply a rough indication of how often porpoises would encounter turbine blades if they took no action to approach or avoid them. Nevertheless this study suggests that, for the two sites at least, porpoise-turbine interactions are likely to be substantially rarer than if turbines had been deployed in other habitats.

Other marine mammal species were seen on the surveys. Most abundant were harbour and grey seals which were seen in high numbers both in the water and hauled-out immediately adjacent to the high-flow areas. A minke whale, bottlenose dolphins and an otter were also observed in the tidal narrows. No basking sharks were seen.

In terms of cetaceans, these surveys indicated that porpoises (as well as other, less frequently encountered cetaceans) did not appear to be particularly abundant within the tidal-streams of Kyle Rhea and the Sound of Islay. These findings notably contrast with results from Wales. Whether these Scottish results are also true for larger tidal-energy sites (such as the Pentland Firth) has yet to be determined.

Furthermore, despite occurring at apparently low densities, we did see and hear porpoises in the tidal streams and it must be remembered that abundance is not the same as ecological importance. The tidal narrows are likely to be used for transit between adjacent water masses and therefore disruption of these passageways may also have wider implications for use of other habitats.

GENERAL INTRODUCTION

The potential to extract energy from tidal-streams offers one of the truly sustainable alternatives to fossil fuel use (MacKay 2008). Furthermore UK coastal waters have a potential to provide substantial quantities of this resource (ABPmer 2008). It is likely that introducing energy extraction machines to coastal waters will have consequences (positive and negative) for the receiving environment. However, because these technologies are new, there is uncertainty over the precise nature and extent of these environmental interactions. As a result, the Scottish Government is exploring a “survey, deploy and monitor” approach to allow a staged introduction of the sector while permitting lessons from environmental and other studies to be incorporated before reaching full-scale developments.

One frequently cited and significant area of uncertainty for the developing marine renewables sector is the possibility of injurious collisions between large vertebrates (marine mammals, sharks, turtles, diving birds) and operating tidal-turbines (Linley et al., 2009). While there are some obvious direct parallels to the collisions that occur between flying vertebrates (birds & bats) and wind turbines (Barrios and Rodriguez 2004), there are also many fundamental differences that mean that direct extrapolations are inappropriate (animal sensory modalities, relative animal to turbine size, blade velocity and so on). Likewise, comparisons with other analogous interactions (whale-ship or fish-power station cooling intake strikes etc.) are also too dissimilar to directly inform us of the nature of the problem.

In an attempt to estimate the potential magnitude of future interactions, modelling work was conducted as part of the Scottish Strategic Environmental Assessment for marine renewables (Wilson et al., 2007).This exercise attempted to determine how often marine mammals and turbines would independently share the same locations in space and time and thus how often interactions (that could lead to collisions) were likely to occur. This encounter model focussed on potential rates of interaction between harbour porpoises (*Phocoena phocoena*) off the west of Scotland and a development of fictitious (but typical) 16 m diameter three bladed turbines. The model predicted that co-occurrences between animals and turbine blades could be relatively common at around thirteen interactions per turbine per year. This model necessarily made a variety of assumptions both about animal behaviour and turbine design but nevertheless the level of potential interaction clearly warrants further investigation. Among the key assumptions was that the density of porpoises in sites of interest for tidal-stream energy extraction are similar to the rest of the west of Scotland (Block ‘N’, 0.394 km^{-2} estimated at that time from the SCANS-II survey, Macleod 2006).

The studies outlined in this current report has focussed on the validity of this density assumption. At present there is uncertainty over whether porpoises either target or avoid marine habitats subject to high rates of tidal flow. Studies carried out in Shetland (Evans 1997), Wales (Calderan 2003; Pierpoint 2008), the Bay of Fundy, north America (Johnston *et al*. 2005), Devon (Goodwin 2008) and, to an extent, western Scotland (Marubini *et al*. 2009) all indicate that porpoises preferentially target / are found in elevated densities in areas of high tidal-streams. In one of the most directed studies of porpoises in a tidal-race environment, Pierpoint (2008) found that porpoises were present in Ramsey Sound (Wales) particularly during the ebb tide and were there for 70% of the observation periods. These animals appeared at highest densities in the area of maximum tidal flow and in water depths between 25 and 57 metres. Likewise Gordon *et al* 2011, compared densities and encounter rates for porpoises at two Welsh tidal current sites with those for other European sites and found them to be amongst the highest reported.

In marked contrast, Embling *et al*. (2010), analysed results from dedicated cetacean surveys from the southern Inner Hebrides. They found that porpoise distribution was best explained by tidal currents with the higher densities predicted in areas of *low* current. A follow-on study encompassing the entire Hebrides (Booth 2010) found that depth (especially waters between 50 and 150 m), steep slopes and proximity to land were all important in explaining areas of high porpoise density. Relationships with current speed were less important than these other variables. In only two of six years of data did current speeds appear important in his modelling work and in these the relationships between current and porpoise occurrence were contradictory (2005: less current, more porpoises, 2008: more current, more porpoises). Given that relationships were not apparent in the other four years of survey effort, Booth considered that if current speed was important it would have to be at scales finer than those his surveys were designed for (i.e.at eddy and tidal rips).

Therefore, the relationship between porpoise occurrence and areas of strong tidal flows remains confused. This is primarily because surveys have either been focussed entirely within areas of strong flow or at larger scales where water-flow characteristics were not a primary consideration in survey design. Accordingly at this time it is difficult to determine how often encounters between porpoises and tidal-stream energy devices are likely to occur. In this project, therefore, we specifically targeted two tidal narrows (Sound of Islay and Kyle Rhea) of interest to the tidal-stream energy sector on the west of Scotland to look specifically at porpoise occurrence. The results would help inform the considerations of how often porpoises are likely to come into close association with tidal-stream energy devices.

For these investigations we used a variety of standard, modified and new techniques to investigate temporal and spatial patterns of porpoise occurrence. Specifically: Section 1 outlines the use and results from conventional boat surveys (using visual and acoustic techniques) adapted for collecting unbiased data in water moving at speeds similar to vessel speed. Our main aim of this effort was to derive comparable estimates of porpoise density in tidal-stream habitats relative to more typical west of Scotland coastal waters. Section 2 describes the use of two new acoustic methods for porpoise detection and tracking that were specifically developed for tidal sites. The aim here was to advance cutting edge acoustic tools so that they could be used in moving water where conventional methods cannot be successfully applied. Section 3 is an overall discussion and considers the implications of these results for rates of interactions between porpoises and tidal-stream energy technologies. Two appendices follow this report. One describes one of the novel acoustic tracking methods in more detail. The second briefly shows the results of further data on porpoise distribution collected outside of this contract work but as a direct result of it.

SECTION 1: HIGH RESOLUTION BOAT SURVEYS OF PORPOISE OCCURRENCE IN AND AROUND TIDAL SITES

1.1 Introduction

There are several well developed methods commonly used to investigate porpoise distribution and abundance. The most versatile and prevalent is the use of moving platforms (Hammond 2010). Of these the two most common platforms are 1)planes from which surfacing animals can be sighted or photographed and 2)vessels such as boats from which surfacing porpoises can be seen or submerged vocalising animals can be acoustically detected. While the former offers the opportunity to rapidly survey large areas (particularly those with complex coastlines), the latter also allows small areas to be surveyed in greater detail, potentially at lower cost and with acoustic methods incorporated. Both aerial and boat-based techniques have been used to examine porpoise occurrence over large areas off the west coast of Scotland (plane: SCANS II survey; boat: Embling et al. 2010 and Booth 2010). Because all of these surveys were synoptic in their design and implementation they did not provide definitive information on how frequently porpoises use highly tidal areas on the west coast of Scotland.

Here we focus on boat-based methods to investigate porpoise occurrence in two discrete areas of immediate interest to the tidal-stream industry. Both of these areas are likely to be developed to test and refine tidal-energy extraction device arrays. The first is the Sound of Islay (between the islands of Islay and Jura,55.840°N -6.098°W). These narrows are around 700 m wide at their most constrained and experience tidal streams to at least 2.6m.s^{-1}. A development of ten Hammerfest Strøm HS1000 one megawatt tidal turbines is currently being progressed by Scottish Power Renewables. The second site is at Kyle Rhea (the narrows between Skye and the mainland 57.236°N -5.660°W). These narrows are approximately 450 m wide at their most constrained and experience tidal streams of at least to 2.3 m.s^{-1}. Two companies have shown interest in this area but site evaluation and environmental consenting are at an earlier stage than the Sound of Islay scheme. Both of these areas are comparable in their size, habitats and tidal-streams and both are likely to become either the world's first or near-first demonstration arrays of full-scale tidal-stream turbines. In terms of surveying, both are directly adjacent to areas of known high porpoise abundance (Booth, 2010) and offer waters that are sufficiently sheltered to allow detailed investigations of porpoise occurrence relevant to the abundance-in-tidal-flow question.

While it may be preferable to survey these relatively small areas using a boat, the strong tidal streams themselves present a significant difficulty. When flowing, the water velocity (2.5 m.s^{-1}) itself becomes a significant proportion of the boat's speed (3.6 - 5 m.s^{-1}). Survey *against* the flow and the vessel will make comparatively little progress over the seabed; survey *with* the flow and the boat will cover much more ground per unit time compared with less tidal areas. These differences are likely to significantly impact the number of porpoises detected. This is because if porpoises orientate relative to the seabed, for example, piloting the boat *with* the flow will cover more ground and so more porpoises will be detected per unit time than otherwise. Conversely if porpoises station with the water column and not the bottom then surveying *against* the water flow will also overinflate the number of porpoises detected. Furthermore, with observation time per unit of sea changing then the probabilities of observing intermittently surfacing animals are also affected. Because our knowledge of harbour porpoise behaviour in tidal areas is rudimentary it is unknown how porpoises behave relative to the water column or bottom in these conditions and therefore the presence, nature and magnitude of the biases described above are unknown. Thus it became necessary for this project to modify existing line transect methods so that they were not overly biased by the water flow problem. In the rest of this section outlines the method we formulated and implemented to counter the flow issue and used it to determine and compare sighting and acoustic detection rates of porpoises in the two tidal narrows sites against adjacent waters known to have high densities of porpoises.

1.2 Methods

The *Hebridean Whale and Dolphin* Trust's 16 m research boat *Silurian* was used to survey both the Sound of Islay and Kyle Rhea. The boat was deployed as a motor boat (134 horsepower single diesel engine) for these surveys and carried a crew of 10. Visual surveys were conducted in daylight hours in sea conditions equivalent to those expected for wind speeds of Beaufort 3 or less. Two visual observers were on watch at all times during surveys. They were positioned on the foredeck at the mast with an eye height of approximately four meters. They each watched ahead of the vessel to 90° either side of port and starboard respectively. Sightings of marine mammals were called on handheld radio down to a third person below decks who ran the computer sightings database (*Logger 2000*, IFAW). This programme continuously logged the boat's GPS track. It also prompted for information on weather and sea conditions every thirty minutes and every time the vessel changed course. The distance to each marine mammal sighting made by the observers was logged along with the bearing from them to the animals and the boat's apparent heading. The real heading was determined from the GPS track and often differed significantly from the boat's apparent heading especially when operating in tidal-streams. Notes were also kept on the species, number, direction of travel and behaviour of the animals sighted. Observers were on watch for a maximum of two hours at a time. The distances estimated by the observers were periodically checked using a laser range finder (Leica Rangemaster 800).

As well as the visual observations, acoustic data were collected by towing a two-element hydrophone array and depth sensor100 m behind the vessel. Porpoise echolocation clicks received by the hydrophone array and amplifiers were sent to a onboard high speed data acquisition card sampling at 500 kHz. This output was streamed to a PC running purpose written software (RainbowClick IFAW; Gillespie, 1997) for real time quality control and recorded along with time and GPS locations on a hard drive for later analysis.

The vessel's survey track was predefined before each day's survey and was intended to survey both the area of tidal interest and less tidal waters to the north or south for comparison. The exact area surveyed was tuned so that the best surface conditions would be encountered given the expected wind conditions and so that the tidal-area itself would be examined in a variety of tidal states (slack low, flood, slack high, ebb). As described in 1.1, using conventional survey methods in tidal-streams (where the water was flowing at speeds that are a sizable proportion of the vessel speed) are likely to result in significant biases. As a result we considered methodological adaptations to reduce tidal-stream specific effects. Surveying with the tidal stream, turning and surveying against it and averaging would be one way to counter any bias but because the tidal flow was a significant fraction of boat speed the against-tide leg would amount to considerably more survey time than the down-tide leg. Furthermore at spring tides, going against the tide would be near impossible for the vessel used. Instead we developed a new method of tacking back and forth across the tidal-stream at an angle so that progress over the seabed equalled progress through the flowing water. Thus porpoises would have equal detection probabilities if they were orientating to the bottom or the water column or (more likely) some combination of the two. Tacking back and forth up-current turned out to be impossible with the rapid rates of flow experienced off Islay and Skye. Instead the boat was piloted across and *with* the flow at an angle of 58° off the downstream direction of the tide. This angle was arrived at after considering the expected average flow rates at these sites during the survey periods and the cruising speed of the *Silurian* (See Gordon *et al*. 2011 for further explanation of this approach).

After the survey the visual sightings were filtered for sea state, site etc. and plotted using GIS. To draw generalisations about porpoise occurrence inside and outside of the tidal stream sites of interest the survey areas were divided into zones which are marked on the maps where appropriate. Acoustic data were analysed using the software package RainbowClick (provided by IFAW; Gillespie, 1997). This package contains click classifiers for harbour porpoise clicks, allowing individual porpoise clicks to be clearly identified. These clicks were subsequently integrated into a large survey database, by matching each click with a specific GPS location along the survey trackline. The survey recorder software was set to record the GPS position every 10 seconds (although in practice this interval sometimes varied due to unexpected technical difficulties). In this manner, clicks were assigned to particular 10-second segments, allowing click rates (clicks/second) to be calculated. It also allowed for the calculation of total number of clicks per km surveyed, once transect lengths were calculated.

1.3 Results

Survey effort was performed in two sessions. In the summer of 2009 we focussed on tidal-stream waters around Sound of Islay. In 2010 we repeated similar survey efforts but this time surrounding the Kyle Rhea narrows 160 km further to the North.

1.3.1 Sound of Islay:

Seven days of survey effort were dedicated to the Sound of Islay and adjacent waters between 2nd and 7th July 2009. The survey vessel *Silurian* was mobilized to and from Oban and completed a total of 534 km of track-line effort. More than three quarters (78%) of this distance was covered by concurrent visual and acoustic observations (Table 1). Most of the rest was either visual only(<1%) or acoustic only (18%) observations. “Off effort” work (3%) primarily involved locating overnight anchorages. Average vessel speed over the ground (recorded at 10 second intervals) was 6.4 knots, with little variation among the different survey modes (Table 2). As expected, the greatest variability occurred during ‘Off effort’ periods.

Table 1. Overall summary of survey effort in and around the Sound of Islay, July 2-7, 2009, by survey type. 'Off effort' involves times when the vessel was manoeuvring to and from intended survey start / end locations from overnight anchorages.

Survey length (km), by survey type					
Date	Acoustic only	Acoustic and visual	Visual only	Off effort	Total length
02/07/2009		64.0	0.5	2.0	66.4
03/07/2009		78.6	3.1	6.1	87.8
04/07/2009		89.0		1.0	90.0
05/07/2009	17.2	65.3		3.2	85.6
06/07/2009	6.2	92.0		1.5	99.8
07/07/2009	73.6	28.8		1.8	104.3
Total	97.0	417.8	3.6	15.6	534.0

Table 2. Average speed (and standard deviations) of the survey vessel during different survey types (aggregated for entire survey). The total number of records per survey type is indicated.

Speeds by survey type	# of records	Average speed (knots)	SD of speed
Acoustic only	3167	6.2	0.9
Acoustic and visual	14127	6.5	0.8
Visual only	136	5.4	1.3
Off effort	793	4.2	2.3
Total	18223	6.4	1.1

The majority of survey effort occurred within the confines of the Sound of Islay (Figure 1). For analytical purposes, the survey area was subdivided into six broad areas (shown on Figure 1), based on a combination of coastline features and bathymetry:

1. Firth of Lorn, broadly from Mull southward to Colonsay;
2. North of Sound of Islay, including waters between Colonsay and Jura;
3. Northern Entrance to the Sound of Islay(between Islay and Jura);
4. Central Channel of the Sound of Islay;
5. Southern Entrance to the Sound of Islay;
6. South of Sound of Islay, including waters in the Sound of Jura

Outward boundaries of Areas 1 and 6 were generalised to encompass the entire survey track, but were otherwise relatively arbitrary in nature. Most survey effort was in Areas 2-5 (the areas of greatest interest) and involved both acoustic and visual survey effort. The bulk of the acoustic-only effort occurred on the voyage back to Oban when weather conditions were inappropriate for visual observations. Visual-only survey effort occurred briefly on two occasions in Areas 2 and 6, respectively.

The ambient sea state was recorded throughout the survey to help indicate the relatively sightability of surfacing cetaceans given ambient conditions. For this surface wave conditions (rather than wind) based on the Beaufort Scale were judged and recorded. This measure therefore included wind against tide occurrences with associated choppy conditions. The weather was favourable for the majority of this survey and most “on effort” survey work (70%) occurred with sea states at or less than Beaufort 3 (Table 3). When sea state deteriorated beyond 4 the visual surveyors were typically stood down but the acoustic surveying was maintained.

Sea state conditions varied by area. Generally, sea states were highest in waters to the north of the Sound of Islay and lowest (70-90% < SS 3) in the Central Channel (which was helpfully also the area of most interest for this study) and the Southern Entrance (Figure 2).

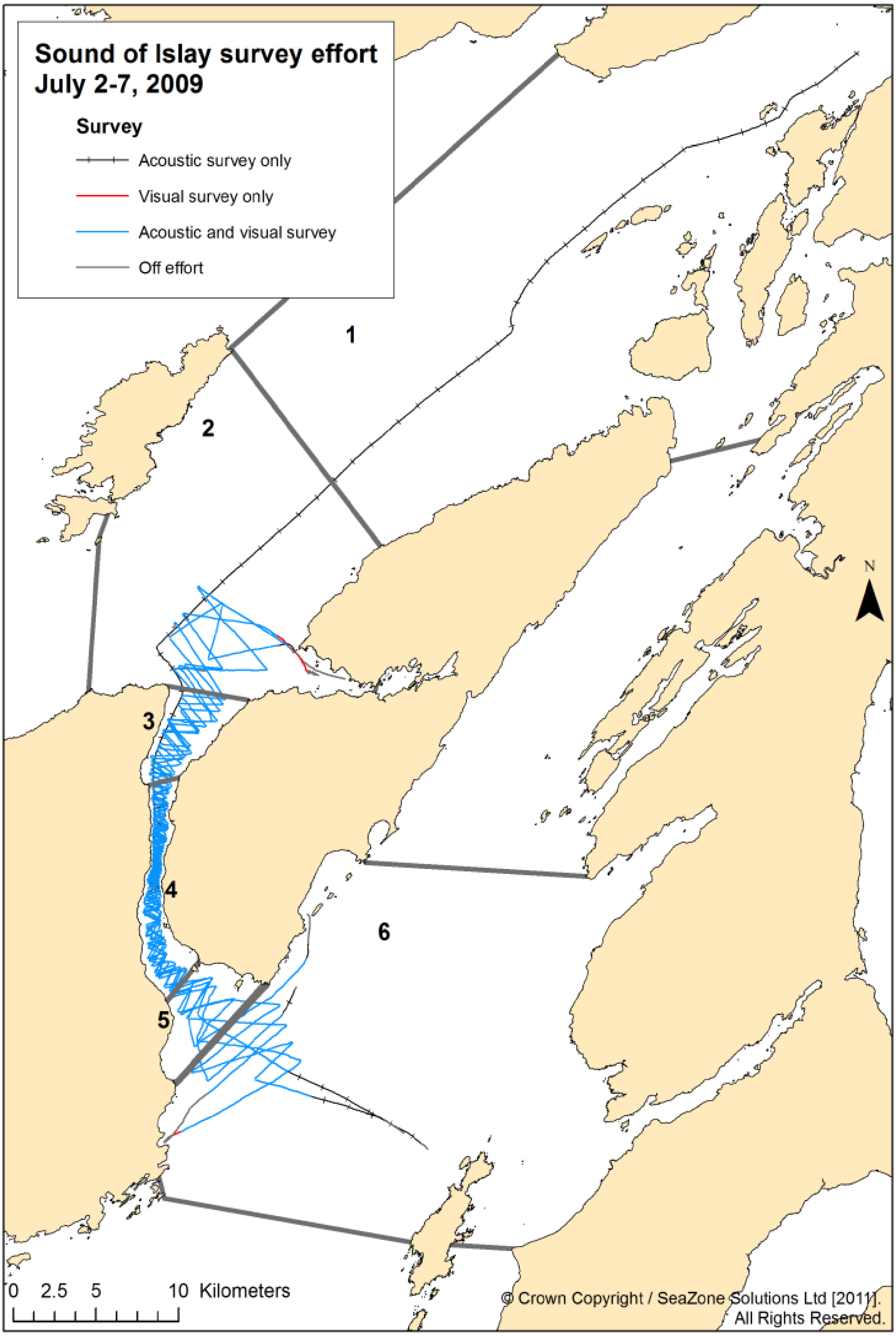

Figure 1. Overview of Sound of Islay survey tracks. Numbered areas include 1) Firth of Lorn; 2) North of Sound of Islay (between Islay and Jura); 3) Northern Entrance; 4) Central Channel; 5) Southern Entrance, and 6) South of Sound of Islay.

Table 3. Lengths of survey transects undertaken at different sea states (aggregated for entire survey).

Transect length (km)	**Sea state (Beaufort scale)**										
Survey type	**0.5**	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**5**	**6**	**Total**
Acoustic only				4.6	3.8	7.8	6.1	26.8	40.7	7.2	97.0
Acoustic & visual	27.5	10.7	55.5	124.5	94.0	33.7	22.1	36.5	13.3		417.8
Visual only			0.5		3.1						3.6
Off effort			0.8		2.1	0.5	0.7				4.1
Total	**27.5**	**10.7**	**56.8**	**129.1**	**103.1**	**41.9**	**28.9**	**63.4**	**53.9**	**7.2**	**522.5**

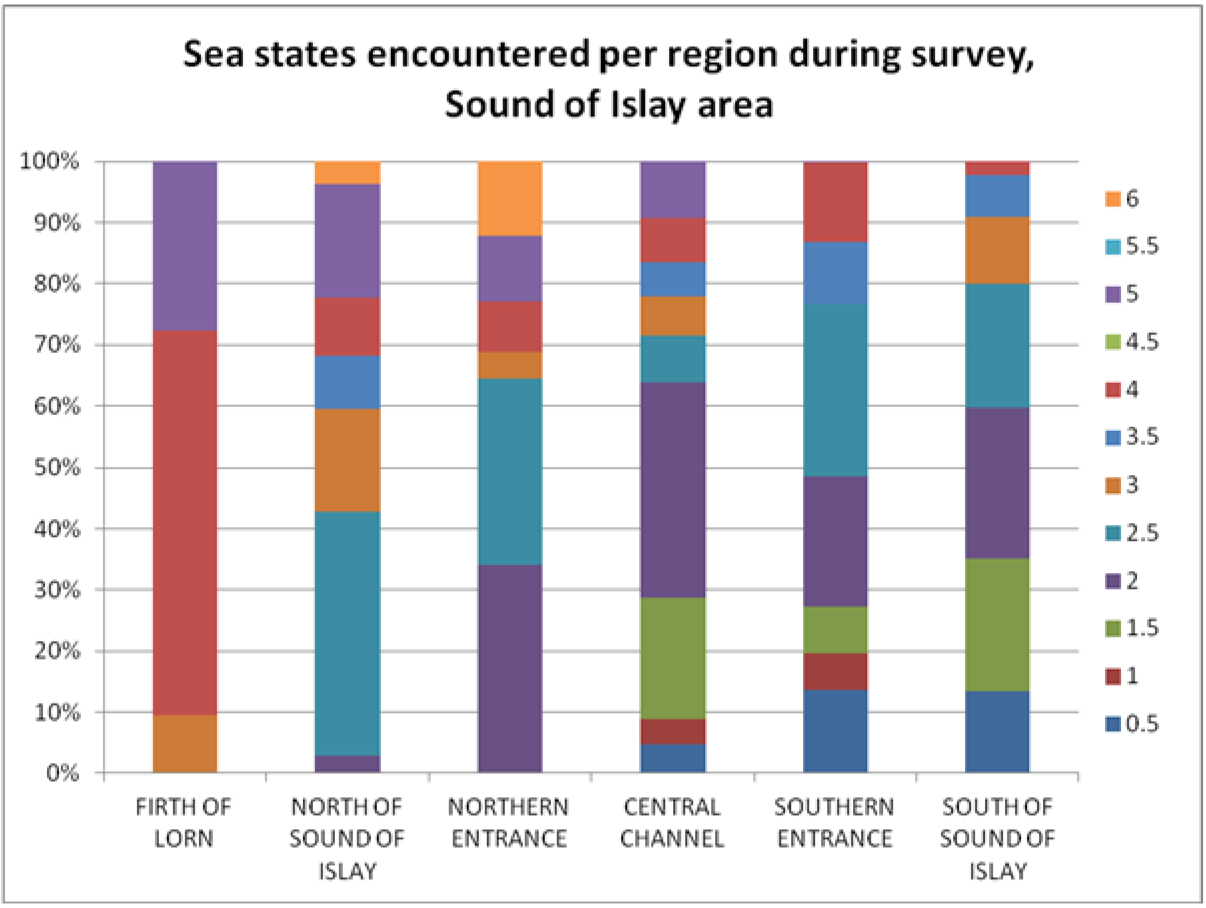

Figure 2. Distribution of total (visual and acoustic) survey effort at different sea states in different areas of the Sound of Islay (arranged from North to South on the x-axis). Higher sea states were most frequently recorded towards the northern part of the survey area.

A total of 60 sighting events (73 individuals) of five marine mammal species were recorded during the visual survey of the Sound of Islay area. The majority of cetacean sightings (89%) were of harbour porpoises (34 individuals) but two minke whales (*Balaenoptera acutorostrata*) and two unidentified dolphins were also seen. Both harbour/common (*Phoca vitulina*) and grey seals (*Halichoerus grypus)* were also seen in the water (Table 4). The "unidentified seals" were also likely to be one or other of these two species. No sightings of any kind occurred at sea states >4 and the majority (81%) occurred in sea states of 2 or less (Table 4).

The spatial distribution of sightings varied from species to species. Harbour porpoises were mainly sighted towards the southern end of the Sound of Islay and beyond, with a single sighting in the Central Channel (involving three animals) and two sightings (involving a single individual and a pair) north of the Sound of Islay (Figure 3A). In contrast, seal sightings were concentrated within the Central Channel area (Figure 3C). There were too few sightings of minke whales or dolphins to infer distribution but it is interesting to note that both were observed in the Central Channel section of the Sound of Islay as well as elsewhere (Figure 3C).

Visual sightings data were further investigated for harbour porpoises to determine whether the distribution of sightings deviated significantly from what might be expected if porpoises were distributed randomly across the area. To do this the relationship between sightings and sea state were investigated in combination with the Kyle Rhea data (see below).

Table 4. Summary of marine mammal sightings, sighting rates (#per km surveyed), and standard deviation (SD) of sighting rates at different sea states during the July 2009 Sound of Islay survey (visual transects only, all areas combined). NB: average sighting rates and SDs were calculated by averaging sighting rates across all transects at each sea state.

Sighting rates per sea state during VISUAL SURVEY		**SEASTATE**											
		0	**0.5**	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**	**Total**
	Transect length (km)	-	27.5	10.7	56.0	124.5	97.1	33.7	22.1	36.5	-	13.3	421.4 km
Harbour porpoise	# of animals sighted		11		5	15	3						34 porpoises
	#/km		0.19		0.07	0.05	0.05						0.04/km
	SD (sightings rate)		0.32		0.42	0.24	0.30						0.25
Minke whale	# of animals sighted					2							2 minkes[1]
	#/km					0.01							0.004/km
	SD (sightings rate)					0.10							0.06
Unidentified dolphin	# of animals sighted				1			1					2 dolphins
	#/km				0.006			0.05					0.005/km
	SD (sightings rate)				0.043			0.26					0.08
Harbour seal	# of animals sighted		1		6	4	2	4					17 seals
	#/km		0.05		0.19	0.04	0.03	0.17					0.06/km
	SD (sightings rate)		0.18		0.59	0.24	0.14	0.92					0.39
Grey seal	# of animals sighted		1	1	3	3							8 seals
	#/km		0.06	0.09	0.07	0.03							0.03/km
	SD (sightings rate)		0.19	0.32	0.28	0.20							0.17
Unidentified seal	# of animals sighted		2	1	3	2	1	1					10 seals
	#/km		0.11	0.07	0.07	0.04	0.01	0.01					0.03/km
	SD (sightings rate)		0.24	0.25	0.31	0.31	0.09	0.06					0.23

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[1] A third minke whale was sighted opportunistically during an acoustics-only transect through Area 1 (see Figure 3B), but was not considered during subsequent analyses.

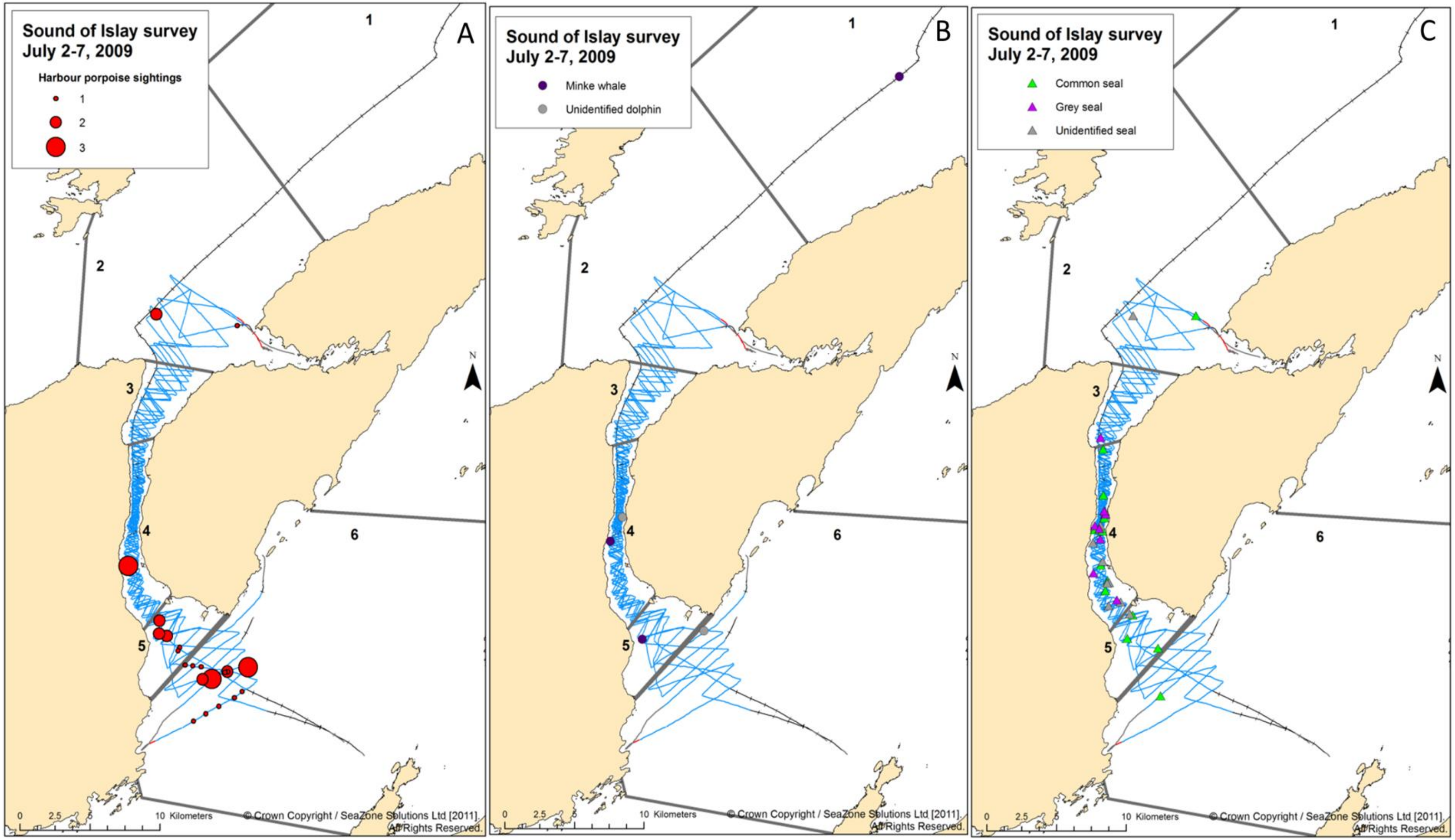

Figure 3. Visual sightings of A) harbour porpoises (group size of each sighting indicated), B) other cetaceans and C) seals, observed during the July 2009 survey of the Sound of Islay area. Most porpoise sightings occurred towards the southern part of the Sound of Islay, whereas most in-water seal observations took place in the central channel of the Sound.

Table 5. Summary of harbour porpoise sightings, sighting rates (# seen per km surveyed), and standard deviation (SD) of sighting rates at different sea states in different areas during the July 2009 Sound of Islay survey (visual transects only).

Harbour porpoise sighting rates per area, per sea state during VISUAL SURVEY		**SEASTATE**											
Area		**0**	**0.5**	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**	**Total**
North of Sound of Islay	# of porpoises						3						3
	Survey length (km)					2.3	30.0	14.1	6.6	8.1		61.2	2.3
	Avg. sighting rate (#/km)						0.20						0.09
	SD (sighting rate)						0.58						0.40
Northern Entrance	# of porpoises												0
	Survey length (km)					27.6	24.6	3.5		6.7		8.1	70.4
	Avg. sighting rate (#/km)												-
	SD (sighting rate)												-
Central Channel	# of porpoises				3								3
	Survey length (km)		9.1	7.8	37.8	67.0	14.6	12.1	10.5	13.5		5.1	177.7
	Avg. sighting rate (#/km)				0.07								0.01
	SD (sighting rate)				0.44								0.19
Southern Entrance	# of porpoises		2			6							8
	Survey length (km)		6.7	2.9	3.7	10.4	13.7		4.9	6.3		0.1	48.7
	Avg. sighting rate (#/km)		0.09			0.28							0.08
	SD (sighting rate)		0.17			0.43							0.25
South of Sound of Islay	# of porpoises		9		2	9							20
	Survey length (km)		11.8		14.4	17.1	14.2	3.9		2.0			63.5
	Avg. sighting rate (#/km)		0.76		0.12	0.53							0.24
	SD (sighting rate)		0.04		0.27	0.50							0.38
Overall	# of porpoises		11		5	15	3						34
	Survey length (km)		27.5	10.7	56.0	124.5	97.1	33.7	22.1	36.5		13.3	421.4
	Avg. sighting rate (#/km)		0.17		0.07	0.05	0.05						0.04
	SD (sighting rate)		0.32		0.41	0.26	0.28						0.25

In addition to the visual surveys, hydrophones were towed behind the boat to pick-up the echolocation signals of porpoises in the vicinity of the survey vessel. These data are similar to sightings in that the presence of porpoises can be deduced. However it is important to note that because porpoises do not echolocate all of the time an absence of detections does not confirm absence. That said acoustic detection is less prone to bias from adverse sea-states so provides parallel perspectives on porpoise distribution. Slightly more acoustic effort was collected than visual because of the sea states during the survey (acoustic: 514, visual: 421 km effort)

As with visual sightings, porpoise clicks were not particularly frequently recorded across the whole study area. Overall, a total of 169 clicks were detected in 45 events, of which a substantial number (n=19) involved the detection of only a single click. As these events could have been artefacts caused by high ambient noise or other non-porpoise sources, they were discarded from further analysis (Table 6).

Table 6. Summary of harbour porpoise click event detections, detection rates (# events per km surveyed), and standard deviation (SD) of detection rates in different areas during the July 2009 Sound of Islay survey (acoustic transects only). Events involving only a single click have been excluded from the bottom half of this table.

Harbour porpoise click events detected during ACOUSTIC survey effort	**Area**						
	Firth of Lorn	**North of Sound of Islay**	**Northern Entrance**	**Central Channel**	**Southern Entrance**	**South of Sound of Islay**	**Total**
Survey length (km)	42.1	77.6	76.4	190.6	48.7	79.4	514.8
# of click events detected	21	1		7	2	14	45
Average detection rate (click events/km)	0.25	0.002		0.03	0.03	0.11	0.03
SD of detection rate (click events/km)	0.34	0.011		0.38	0.11	0.29	0.31
# of click events detected (>1click per event)	11			4	1	10	26
Average detection rate (click events/km, >1 click per event)	0.13			0.02	0.01	0.09	0.02
SD of detection rate (click events/km, >1 click per event)	0.18			0.24	0.07	0.24	0.20

Remaining click events were used to calculate click rates (clicks per second) for each point along the transect where such an event was detected (Figure 6). For each click event, the number of clicks within each time period from one GPS position reading to the next (typically 10 seconds) was calculated to generate an average click rate (clicks/second). All such click rates were aggregated according to surveyed area and plotted in 1 click/second bins (Figure 5). Sea states were not found to have an obvious impact on acoustic detection rates. Generally speaking, click rates were low in all areas, rarely exceeding 1 click/second.

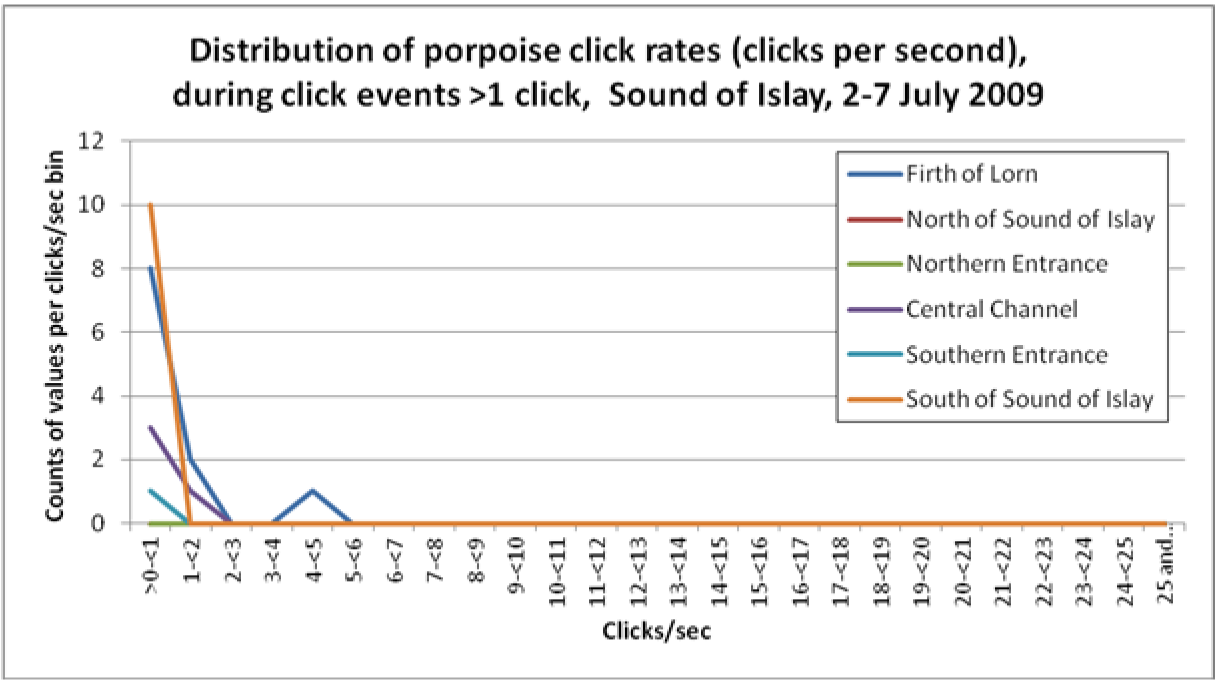

Figure 4. Frequency distribution of harbour porpoise click rates at events involving >1click, as detected during the acoustic survey of the Sound of Islay area, July 2009. Note that detection rates are quite low overall.

As with sightings, the distribution of porpoise click event detections in the areas immediately surrounding the Sound of Islay varied from one area to another (Figure 6). Most click events were recorded in the Firth of Lorne during the return voyage to Oban at the end of the survey, in an area where porpoises have regularly been reported in the past (Booth 2010). There were no click events (involving >1 click) detected anywhere around the northern section of the Sound of Islay, with a small number of events detected in the Central Channel itself and more in areas 5 and 6 further south. When the two independent methods of visual and acoustic detections were superimposed, the distribution of both broadly correspond (Figures 7 & 8). Because the acoustic methods are less prone to interference from sea conditions, the coincidence of results from these two independent techniques suggest that the finding of a predominantly southern distribution pattern derived from the visual sightings was not an artefact of just the sea conditions at the time of the survey.

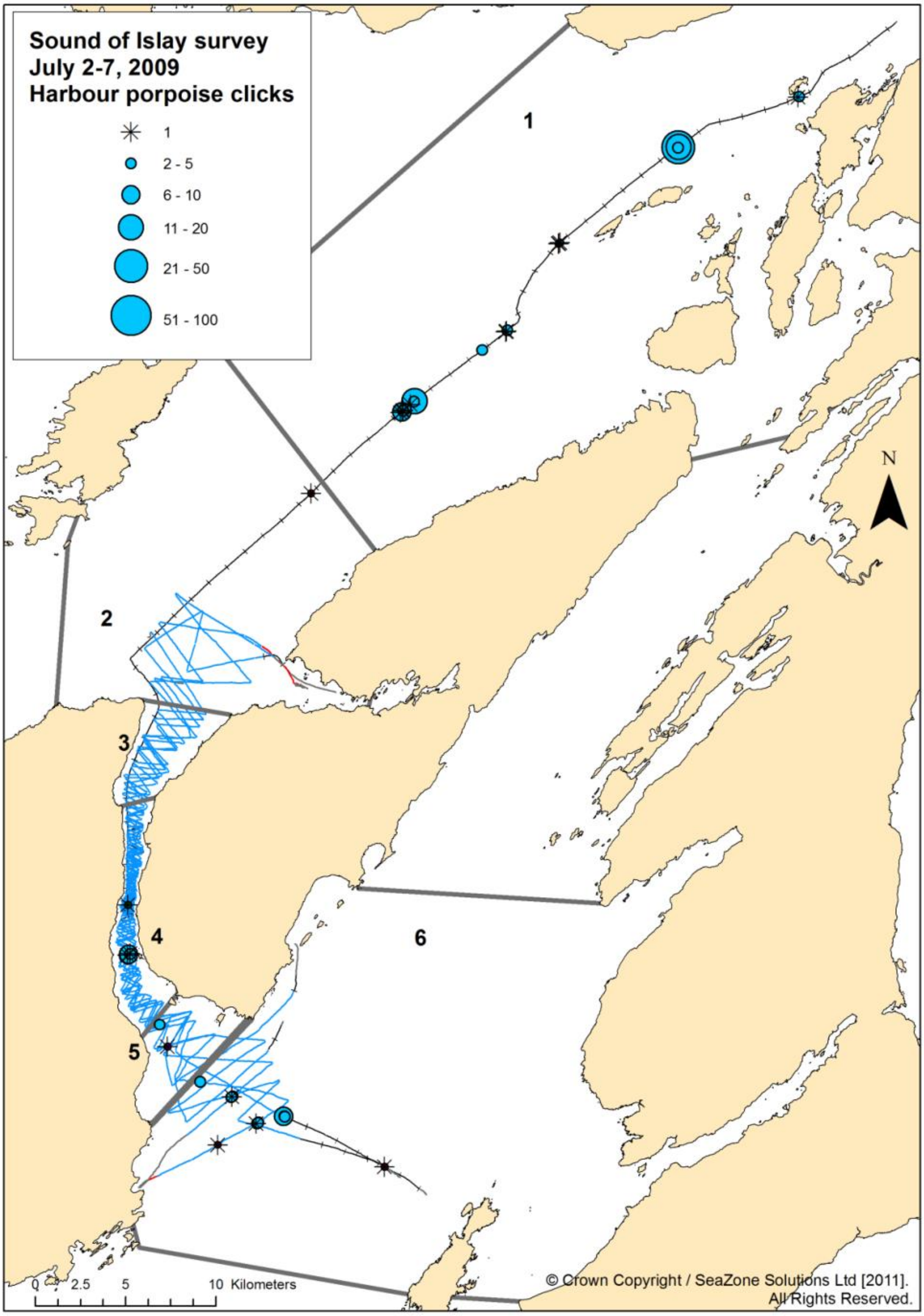

Figure 5. Acoustic detections of harbour porpoise clicks recorded during the July 2009 survey of the Sound of Islay area. Asterisks denote events where only single clicks were recorded (which might have been artefacts caused by background noise).

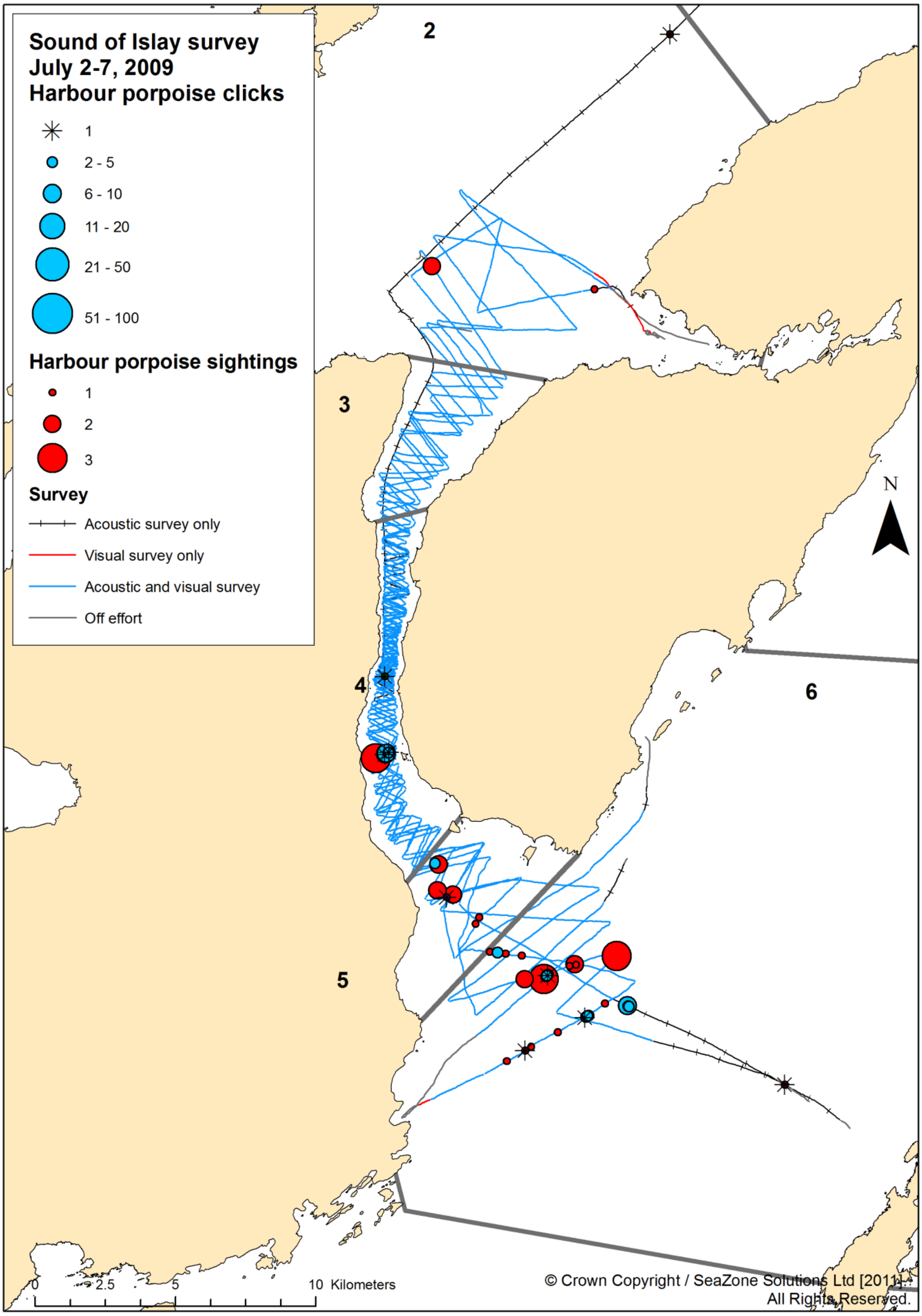

Figure 6. Detailed view of distribution of harbour porpoise sightings and click detections within the Sound of Islay area. Visual and acoustic observations were closely correlated in several instances. The concentration of observations towards the southern end of the Sound of Islay is notable.

1.3.2 Kyle Rhea

We performed nine days of survey effort in and around the Kyle Rhea area on-board the *Silurian* between May 13 and May 21 2010.The survey ran out of Tobermory on Mull with a primary focus on the Kyle Rhea but also included significant effort in the Sound of Sleat, some in Loch Alsh and a small amount in Loch Duich. A total of 776 km of track line was surveyed during this period, with concurrent visual and acoustic observations collected during the vast majority (78%) of the time spent “on effort” surveying which itself accounted for 84% of the distance covered (Table 7).

Table 7. Overall summary of survey effort in the Kyle Rhea, May 13-21 2010, by survey type. ‘Off effort’ involved times when the vessel was manoeuvring to and from intended survey start / end locations from overnight anchorages or during the vertical array trials (see Section 2).

Survey length (km), by survey type					
Date	**Acoustic only**	**Acoustic and visual**	**Visual only**	**Off effort**	**Total length**
13/05/2010	69.3			30.3	99.6
14/05/2010	14.4	77.6	2.6	10.6	105.3
16/05/2010	19.2	62.4		10.6	92.2
17/05/2010	0.8	43.2		27.0	71.0
18/05/2010	22.8	19.7		15.1	57.6
19/05/2010		115.2	5.4	6.1	126.7
20/05/2010	10.4	79.5		17.9	107.8
21/05/2010		112.0		3.6	115.6
Total	**136.9**	**509.8**	**8.0**	**121.2**	**775.9**

Average vessel speed, recorded at 10-second intervals, was 5.0 knots, with little variation among different survey types and significantly lower speeds during “Off effort” transects (Table 8). As in the Sound of Islay survey, the greatest variability occurred during ‘Off effort’ periods which involved a range of vessel movements unrelated to the actual survey.

Table 8. Average speeds, and standard deviations (SD), of the survey vessel Silurian during different survey types (aggregated for entire survey). The total number of records (GPS locations at 10-second intervals) per survey type is indicated.

Speeds by survey type	**# of records**	**Average speed**	**SD of speed**
Acoustic only	4702	6.2	1.3
Acoustic and visual	21082	5.8	2.1
Visual only	282	5.7	1.1
Off effort	9224	2.5	2.6
Total	**35290**	**5.0**	**2.6**

For analytical purposes, the survey area was subdivided into four broad areas (see Figures 8 and 9 for boundaries and place names) based on a combination of coastline features and bathymetry:

1. Loch Alsh/Loch Duich (north of the Central Channel of Kyle Rhea);
2. Central Channel of Kyle Rhea (from the northern entrance south to Bernera Bay beyond the southern entrance);
3. Sound of Sleat North (the area immediately south of the Central Channel of Kyle Rhea, down to the Sandaig Islands);
4. Sound of Sleat – Mull Approaches (the remaining southern portion of the Sound of Sleat, as well as waters between Ardnamurchan and the Small Isles and the Sound of Mull that were traversed on the way to/from Kyle Rhea)

Outward boundaries of Areas 1 and 4 were generalised to encompass the entire survey track, but were otherwise arbitrary. Most survey effort in Areas 1, 2 and 3 (the areas of greatest interest) involved both acoustic and visual survey effort. Due to weather a considerable amount of acoustic-only effort was collected on the voyage out from Tobermory to Kyle Rhea on the first survey day. Due to technical difficulties visual-only survey effort occurred briefly on three occasions in Areas 1 and 4 (2 transects). Area 4 was by far the largest area and the absolute majority of survey effort occurred within its boundaries (Figures 7 and 8).

As with the Sound of Islay, the ambient sea state was recorded throughout the survey to help indicate the relatively sightability of surfacing cetaceans given local surface conditions. The weather was generally more favourable with 92% of surveying being conducted in waters of sea state 3 or less (Table 9).

Table 9. Lengths of survey transects undertaken at different sea states (aggregated for entire survey).

Transect length (km)		**Sea state**								
Survey type	**0**	**0.5**	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**Total**
Acoustic only	0.1	10.4	0.4		20.5	45.4	12.9		46.7	136.4
Acoustic & visual	76.2	120.5	62.0	71.5	76.3	69.1	26.7	4.8	1.5	508.7
Visual only				5.4						5.4
Off effort	12.4	8.5	4.4	28.7	27.6	11.1	9.8		6.0	108.3
Total	**88.6**	**139.4**	**66.8**	**105.6**	**124.4**	**125.6**	**49.4**	**4.8**	**54.2**	**758.9**

Sea state conditions varied by area both because of the boat’s position as weather systems passed over but also due to wind against tide circumstances. This was particularly apparent in the *Sound of Sleat North* area where the ebbing tide from the Kyle Rhea met the Sound of Sleat and its long south-westerly fetch (Figure 9). During periods of particularly strong south westerly winds we took the opportunity to survey Loch Alsh and Loch Duich instead. No survey effort was undertaken in sea states>4.

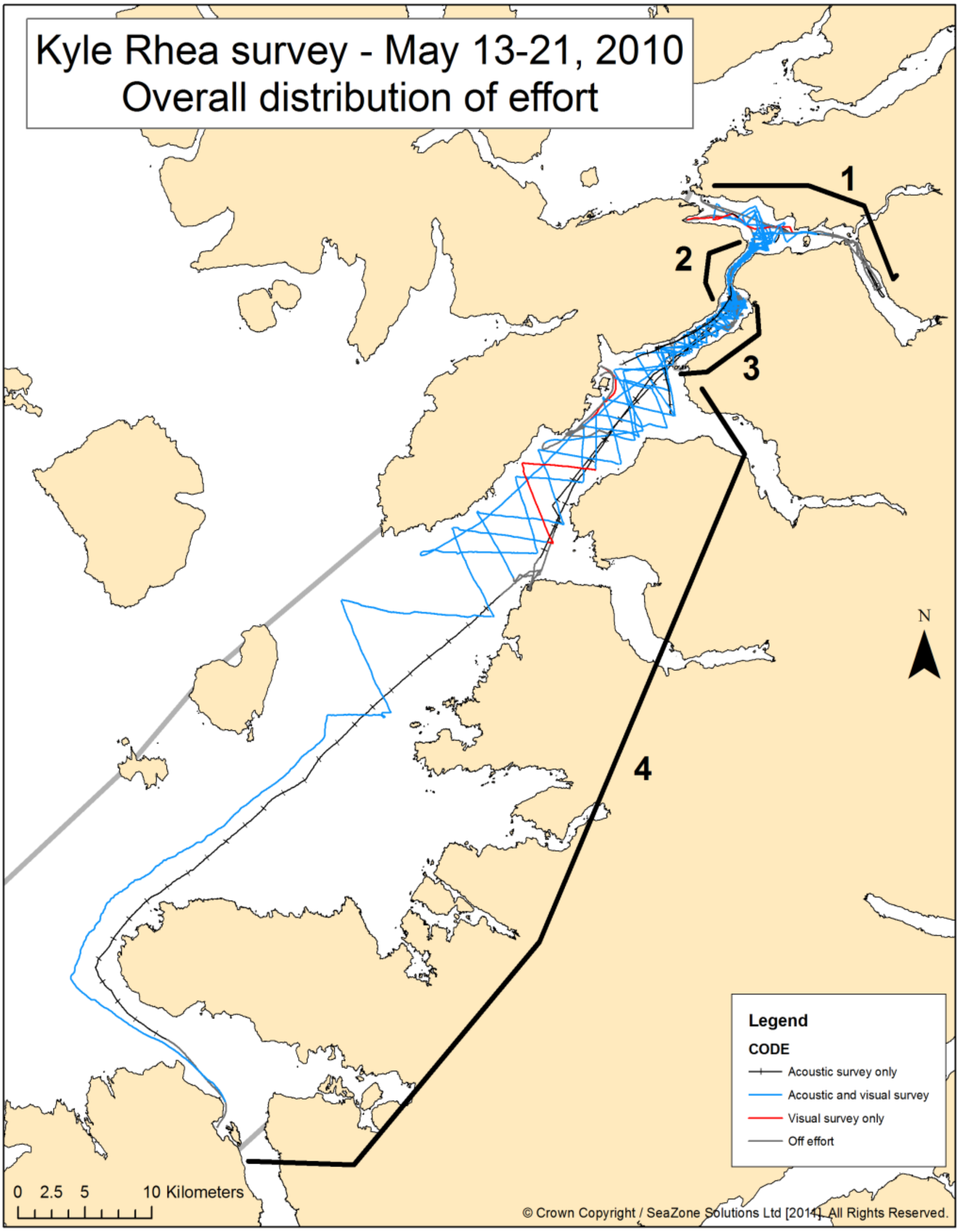

Figure 7. Overview of survey track in and around Kyle Rhea area. Numbered areas include 1Loch Alsh/Loch Duich; 2) Central Channel of Kyle Rhea; 3) Sound of Sleat North; 4) Sound of Sleat – Mull Approaches. Dark grey boundaries delineate different Areas discussed in the text.

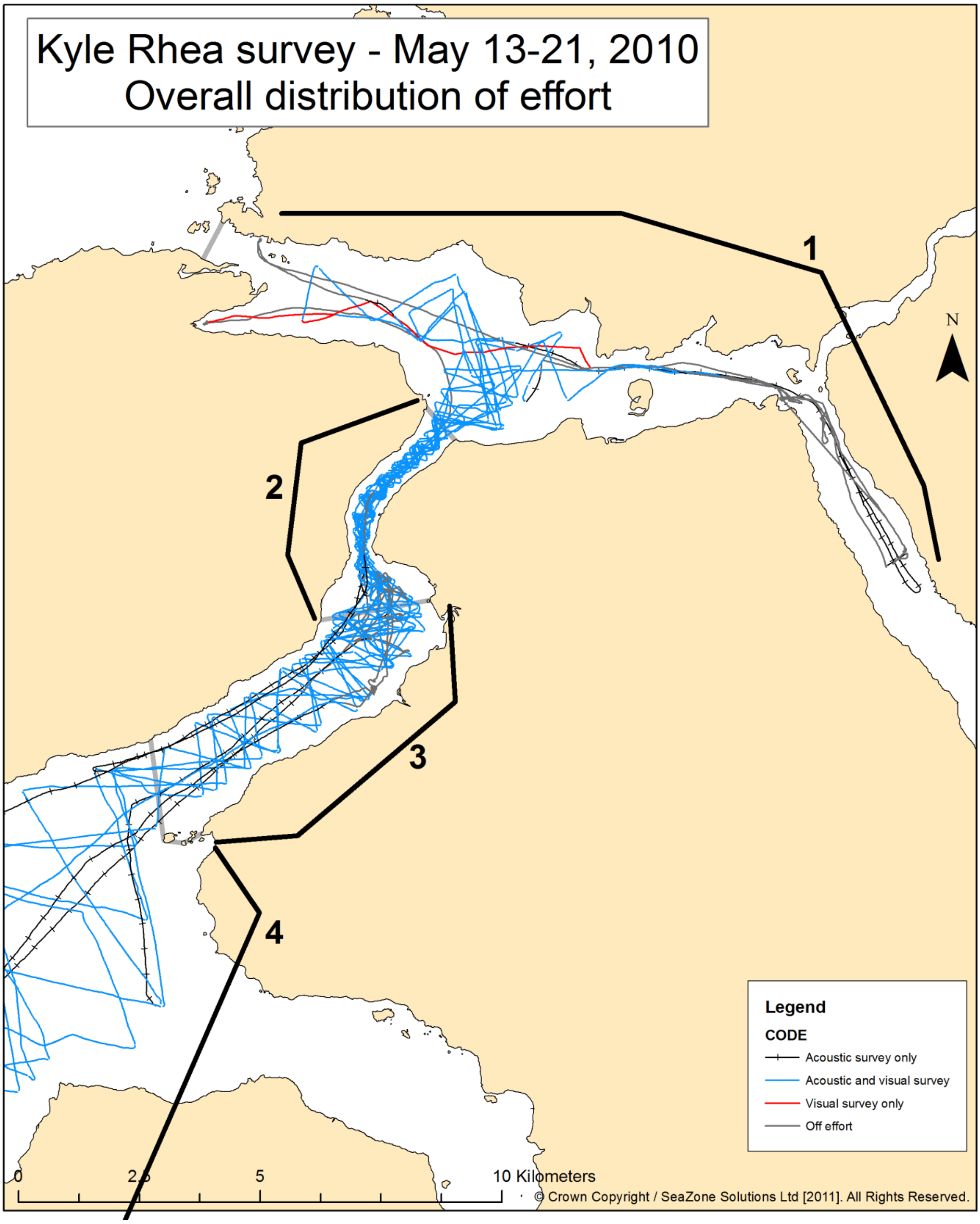

Figure 8. A higher resolution overview of survey tracks in and around the Kyle Rhea area. Numbered Areas include 1Loch Alsh/Loch Duich; 2) Central Channel of Kyle Rhea; 3) Sound of Sleat North; 4) Sound of Sleat – Mull Approaches. Dark grey boundaries delineate different Areas discussed in the text.

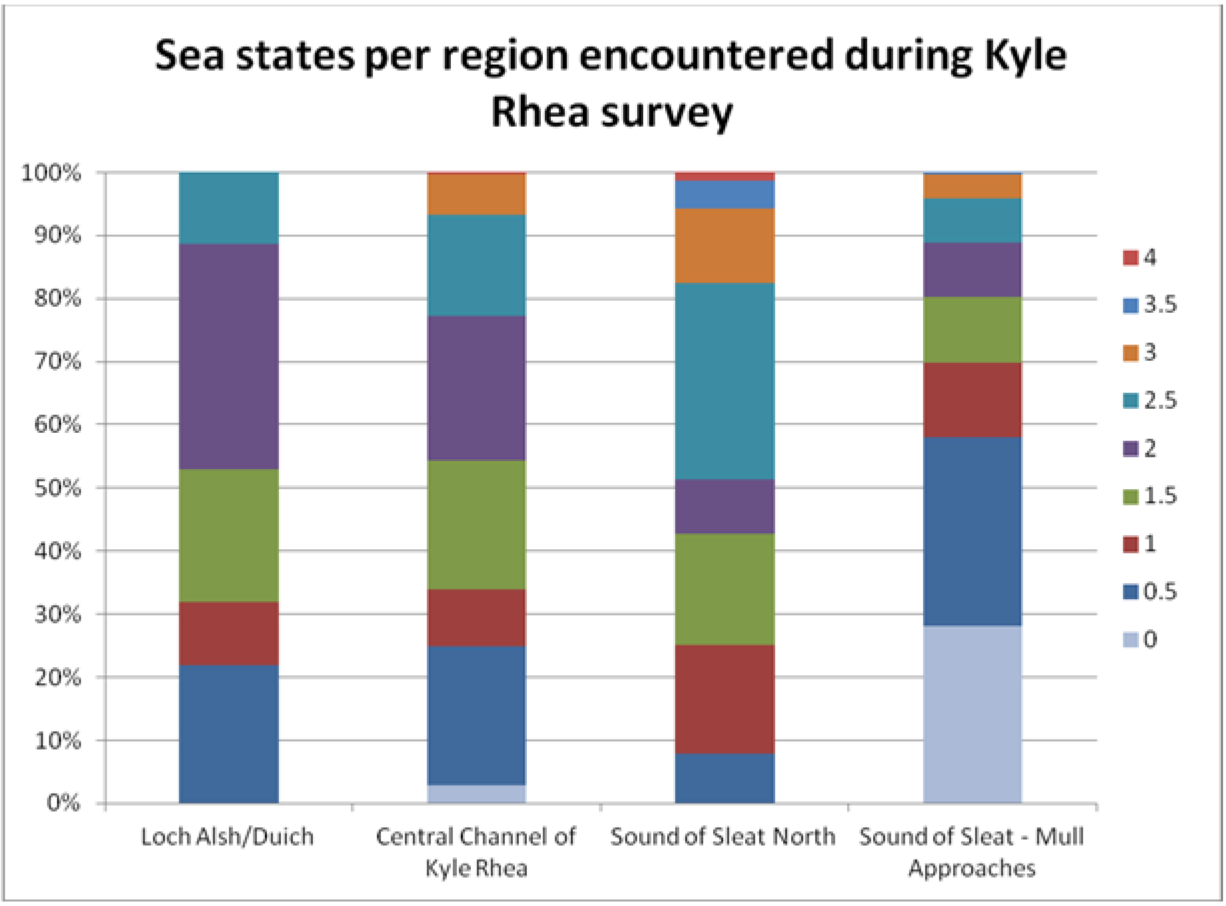

Figure 9. Distribution of total (visual and acoustic) survey effort at different sea states in areas of the Kyle Rhea area (arranged from North to South on the x-axis). Higher sea states were most frequently recorded within the central parts of the survey area where wind against tide conditions were frequent.

A total of 338 individuals were recorded during the visual survey of the Kyle Rhea area, involving four different species, including harbour porpoise, harbour/common seal, grey seal and a single swimming otter (*Lutra lutra*, Table 10). Some seal sightings could not be conclusively identified to harbour or grey and were recorded as *Unknown Seal*. Overall, harbour porpoises and harbour seals were the most frequently encountered species. A further 8 sightings (involving a total of 14 harbour porpoises) were made opportunistically during acoustics-only transects or during off-effort periods, but were not considered during subsequent analyses. The vast majority (90%) of sightings occurred in sea states of 2 or less.

Table 10. Summary of marine mammal sightings, sighting rates (# seen per km surveyed), and standard deviation (SD) of sighting rates at different sea states during the May 2010 Kyle Rhea survey (visual transects only, all areas combined). NB: average sighting rates and SDs were calculated by averaging sighting rates across all transect segments with a particular sea state, however short.

Sighting rates per sea state during VISUAL SURVEY		**SEASTATE**										
		0	**0.5**	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**Not recorded**	**Total**
Transect length (km)		76.2	120.5	62.0	77.0	76.3	69.1	26.7	4.8	1.5	3.6	517.8 km
Harbour porpoise	# of animals sighted	33	30	16	4	3	6	-	-	-	-	92 porpoises
	Avg. sighting rate (#/km)	0.36	0.10	0.09	0.04	0.03	0.06	-	-	-	-	0.07/km
	SD (sightings rate)	0.66	0.27	0.28	0.23	0.17	0.26	-	-	-	-	0.27
Common seal	# of animals sighted	6	44	26	43	28	11	1	-	1	-	160 seals
	Avg. sighting rate (#/km)	0.56	0.75	0.66	0.84	0.50	0.37	0.07	-	1.03	-	0.57/km
	SD (sightings rate)	1.54	3.05	1.73	2.34	1.39	1.53	0.37	-	1.78	-	2.00
Grey seal	# of animals sighted	1	8	8	16	7	3	-	-	1	-	44 seals
	Avg. sighting rate (#/km)	0.006	0.13	0.24	0.36	0.10	0.08	-	-	1.03	-	0.16/km
	SD (sightings rate)	0.025	0.48	0.61	1.09	0.59	0.46	-	-	1.78	-	0.68
Unidentified seal	# of animals sighted	6	10	3	6	5	10	1	-	-	-	41 seals
	Avg. sighting rate (#/km)	0.51	0.08	0.08	0.12	0.09	0.21	0.13	-	-	-	0.13/km
	SD (sightings rate)	1.26	0.38	0.34	0.53	0.49	1.00	0.71	-	-	-	0.64
Otter	# of animals sighted	-	-	-	-	-	1	-	-	-	-	1 otter
	Avg. sighting rate (#/km)	-	-	-	-	-	0.03	-	-	-	-	0.005/km
	SD (sightings rate)	-	-	-	-	-	0.25	-	-	-	-	0.100

There were no absolute patterns of geographical distribution between species across the survey area (Figures 10 and 11). Most porpoise sightings occurred within the *Sound of Sleat – Mull Approaches* area. Around the *Kyle Rhea* itself, porpoises were seen predominantly in the *Sound of Sleat North* and though they clearly use the *Central Channel of Kyle Rhea* only one sighting occurred despite much effort and more than half of this in near-ideal sea conditions (sea state ≤1.5, Figures 10 & 11). Seal sightings occurred throughout the survey but were very abundant in the *Central Channel of Kyle Rhea* (Figure 11). The otter was seen swimming in open water in the *Central Channel of Kyle Rhea* (Figure 11).

For harbour porpoise, sightings data were stratified spatially to determine whether the distribution of sightings varied significantly from what might be expected if porpoises were distributed randomly across the area (Table 11). Sighting rates were highest in the *Sound of Sleat – Mull Approaches* area, and lowest in the *Central Channel of Kyle Rhea*. Sighting rates in Loch Alsh and Loch Duich were somewhat lower than anticipated given historic observations of porpoises in this area. In the immediate area around the *Central Channel of Kyle Rhea*, highest sighting rates were recorded in the *Sound of Sleat North*.

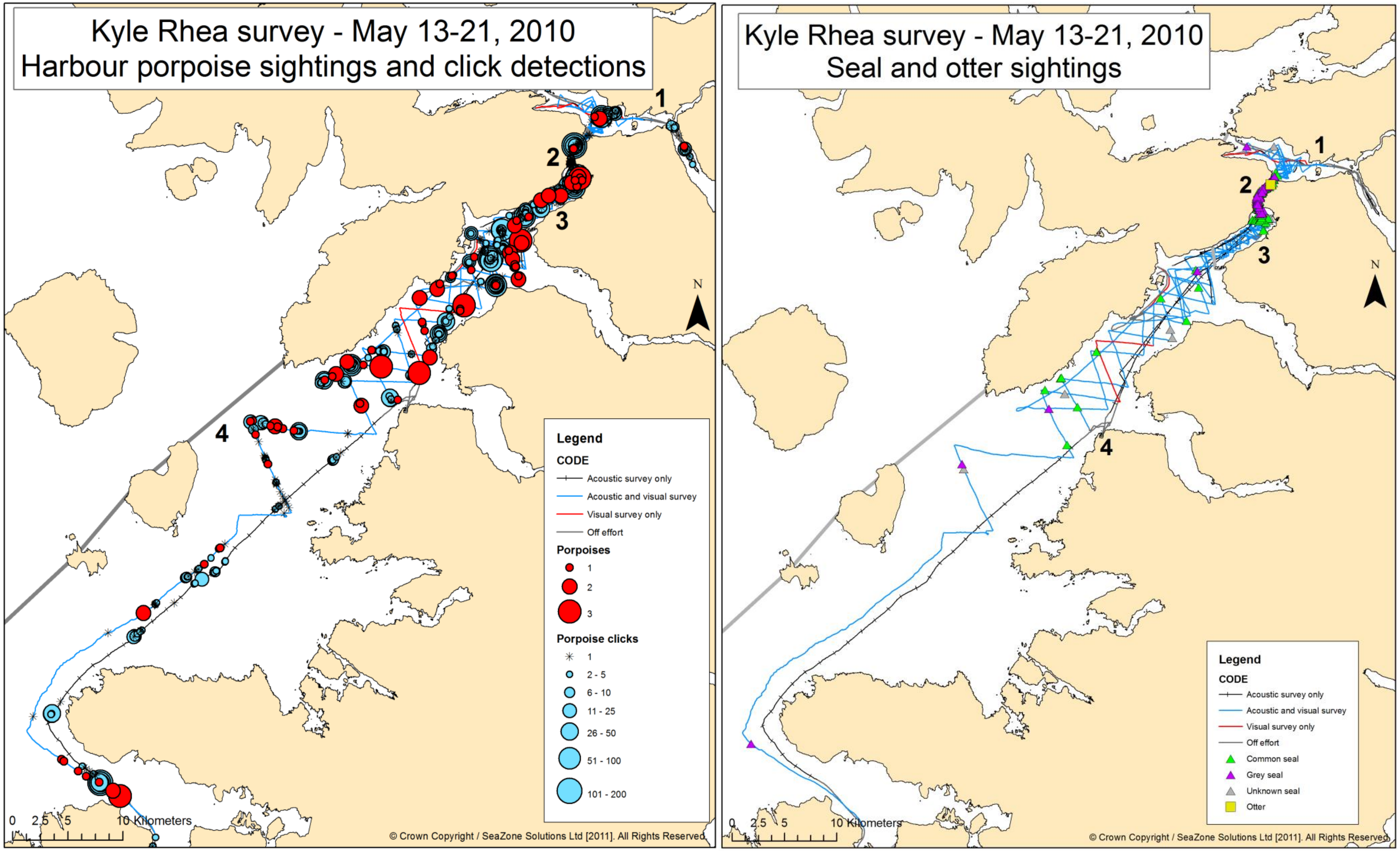

Figure 10. A general overview of marine mammal sightings and porpoise click detections in and around the Kyle Rhea area. Porpoises were encountered more frequently in the Sound of Sleat (particularly Sound of Sleat North), whereas most seal sightings occurred within the Central Channel of Kyle Rhea.

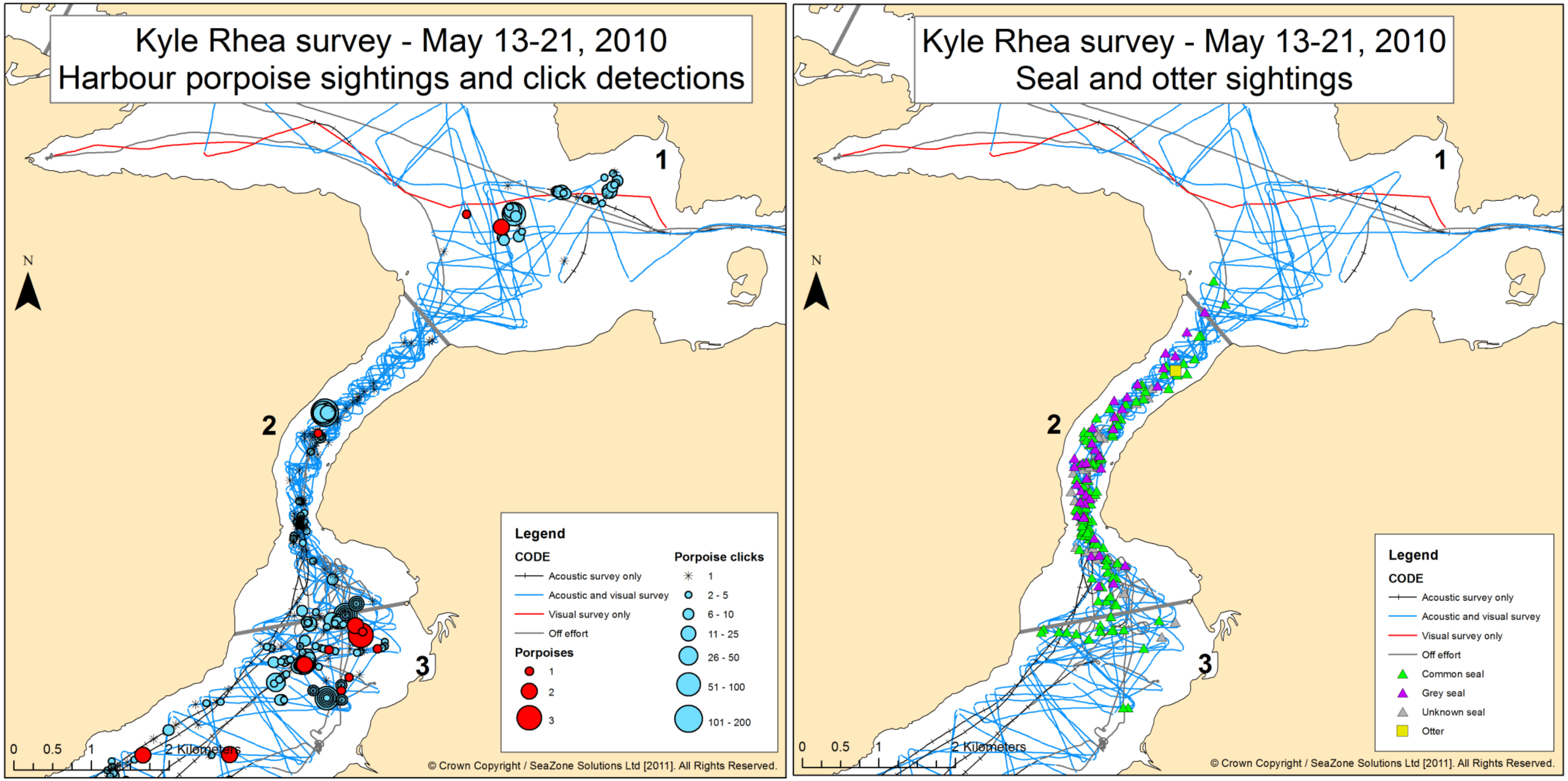

Figure 11. A more detailed look at marine mammal sightings and porpoise click detections in the immediate Kyle Rhea area. Numbered Areas are described in the text. Within this area, porpoises were encountered more frequently in the Sound of Sleat (particularly Sound of Sleat North, immediately south of the Central Channel), whereas most seal sightings occurred within the Central Channel of Kyle Rhea. Click events detected within the Central Channel itself typically involved only small numbers of clicks.

Table 11. Summary of harbour porpoise sightings, sighting rates (# seen per km surveyed), and standard deviation (SD) of sighting rates at different sea states in different areas during the May 2010 Kyle Rhea survey (visual transects only).

Harbour porpoise sighting rates per area, per sea state during VISUAL SURVEY		**SEASTATE**										
Area		**0**	**0.5**	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**Not recorded**	**Total**
Loch Alsh/Loch Duich	# of porpoises					1	2					3
	Survey length (km)		15.8	7.2	15.1	25.6	8.2				3.6	75.4
	Avg. sighting rate (#/km)					0.04	0.12					0.03
	SD (sighting rate)					0.21	0.38					0.19
Central Channel of Kyle Rhea	# of porpoises						1					1
	Survey length (km)	2.5	19.5	8.0	18.0	20.1	14.1	5.5		0.3		88.0
	Avg. sighting rate (#/km)						0.05					0.01
	SD (sighting rate)						0.25					0.10
Sound of Sleat North	# of porpoises		2	2	3		3					10
	Survey length (km)		7.2	16.1	16.4	8.0	28.9	10.9	4.2	1.2		92.9
	Avg. sighting rate (#/km)		0.26	0.10	0.21		0.07					0.09
	SD (sighting rate)		0.50	0.36	0.55		0.25					0.32
Sound of Sleat – Mull Approaches	# of porpoises	33	28	14	1	2						78
	Survey length (km)	73.7	78.0	30.8	27.5	22.6	17.9	10.2	0.6			261.4
	Avg. sighting rate (#/km)	0.53	0.28	0.26	0.01	0.19						0.22
	SD (sighting rate)	0.75	0.37	0.39	0.05	0.41						0.44
Overall	# of porpoises	33	30	16	4	3	6					92
	Survey length (km)	76.2	120.5	62.0	77.0	76.3	69.1	26.7	4.8	1.5	3.6	517.8
	Avg. sighting rate (#/km)	0.36	0.10	0.09	0.04	0.03	0.06					0.07
	SD (sighting rate)	0.66	0.27	0.28	0.23	0.17	0.26					0.27

As with the Sound of Islay survey porpoise-like clicks were recorded throughout the Kyle Rhea acoustic survey. A total of 5,301 clicks were detected in 765 events across all areas. The distribution of these porpoise click events in the areas immediately surrounding the Kyle Rhea area varied considerably from one area to another (Figures 10 and 11). There were particularly frequent click detections in the northern part of the Sound of Sleat, immediately south of Kyle Rhea, as well as locally within the *southern Sound of Sleat* and *Loch Alsh/Loch Duich*. Within the *Central Channel of Kyle Rhea* itself most click events consisted of only small numbers of clicks per event with the majority probably being an artefact of background noise. However there was one recognisable echolocation train. This result is consistent with the visual observations and suggests that porpoises do occur in the narrows but at low densities. Porpoise clicks were frequently detected in the area immediately to the south (*Sound of Sleat North*) as well as elsewhere within the greater Sound of Sleat area. Detection rates were lower than expected in the Loch Alsh/Loch Duich area given that this was a site historically targeted for its high incidence of porpoises in order to develop porpoise detection methodologies (Goodson et al., 1997).

Undoubtedly some of the single click events detected during these surveys were artefacts of ambient noise. So if all 287 single click events are excluded a less sensitive but cleaner picture of porpoise acoustic presence is revealed (lower half of Table 12).

Table 12. Summary of porpoise-like click detections, detection rates (# events per km surveyed), and standard deviation (SD) of detection rates in different areas during the May 2010 Kyle Rhea survey. Events involving only a single click have been excluded from the bottom half of this table.

Harbour porpoise click events detected during ACOUSTIC survey effort	**Area**				
	Loch Alsh/ Loch Duich	**Central Channel of Kyle Rhea**	**Sound of Sleat North**	**Sound of Sleat – Mull Approaches**	**Total**
Survey length (km)	88.8	91.0	117.0	349.9	646.7
# of click events detected	51	112	244	358	765
Average detection rate (click events/km)	0.26	5.40	6.64	1.07	3.96
SD of detection rate (click events/km)	0.90	60.09	42.40	1.48	43.54
# of click events detected (>1click per event)	35	30	179	234	478
Average detection rate (click events/km, >1 click per event)	0.17	0.20	5.41	0.73	1.44
SD of detection rate (click events/km, >1 click per event)	0.70	0.81	37.61	1.32	17.76

Once single clicks had been excluded, the remaining click events were used to calculate click rates along transects. For each click event, the number of clicks within each time period from one GPS position reading to the next (typically 10 seconds) was calculated to generate the click rate (clicks/second). All such click rates were aggregated according to the surveyed area and plotted in 1 click/second bins (Figure 12). Sea states were found to have no apparent impact on acoustic detection rates. Generally speaking, click events were less common (~1 event every 5 km) in more northerly areas (Loch Alsh / Loch Duich and Central Channel of Kyle Rhea) and more common in the southern Sound of Sleat (~3.6 every 5 km) and much more common in the northern Sound of Sleat (~27 every 5 km).

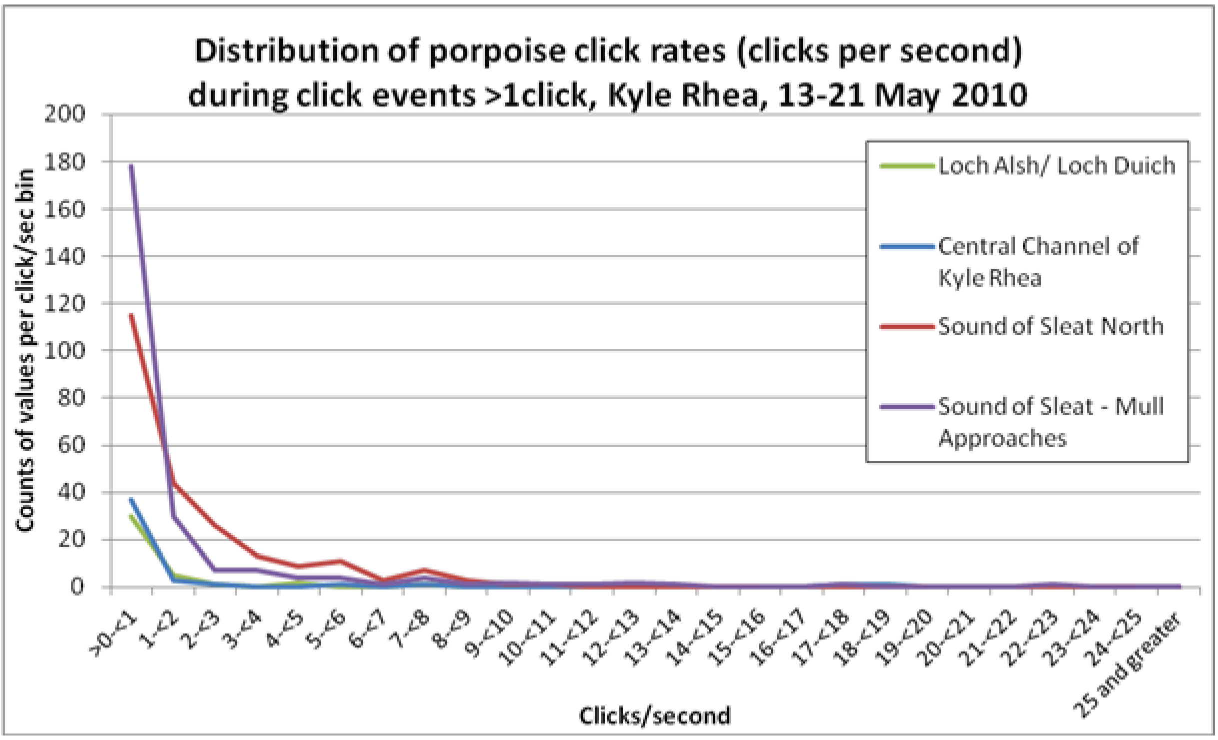

Figure 12. Frequency distribution of harbour porpoise click rates at events involving >1click, as detected during the acoustic survey of the Kyle Rhea area, May 2010. Note that detection rates are quite low in more northerly areas, and increase further to the south in the Sound of Sleat areas.

1.3.3 Comparing results between surveys

The two surveys were carried out in distant but geographically similar areas on western Scotland. Both sites are of interest to the tidal-stream energy sector and at the heart of each is a long, relatively smooth tidal narrows with open, deeper water at either end. The surveys were designed to survey the narrows for porpoise occurrence and the waters either side for comparison. To optimise our opportunities for favourable weather, both surveys were conducted in summer (Sound of Islay: early-July, Kyle Rhea: mid-May) of consecutive years and both covered similar distances of visual survey effort (421: 581 km). The weather in both sites was mixed but overall relatively good and slightly better on the Kyle Rhea July survey.

Furthermore a slightly longer survey trip in the latter allowed us to avoid periods of adverse weather (including blizzards) by engaging in other activities (see Section 2).

As is well established from other harbour porpoise visual surveys, the chance of seeing porpoises is highly influenced by sea conditions, primarily the smoothness of the surface ("sea state"). The magnitude of this effect varies by survey platform and because the same boat was used in both surveys the results from the two sites are directly comparable. Indeed when the sighting rate and sea state from the two surveys were compared the expected relationship was apparent and similar in both (Figure 13). A total of 126 porpoises were seen during these surveys, but no sightings occurred in sea states >2.5, and over half (74 animals) were seen in sea state <1. The strength of this relationship means that simply summing sightings (regardless of weather) is misleading. Accordingly, sightings from the visual surveys were displayed in Tables 5 and 10 stratified by sea conditions. There were no obvious changes in porpoise group sizes detected at higher sea states (all sightings on these surveys involved 1 to 3 animals).

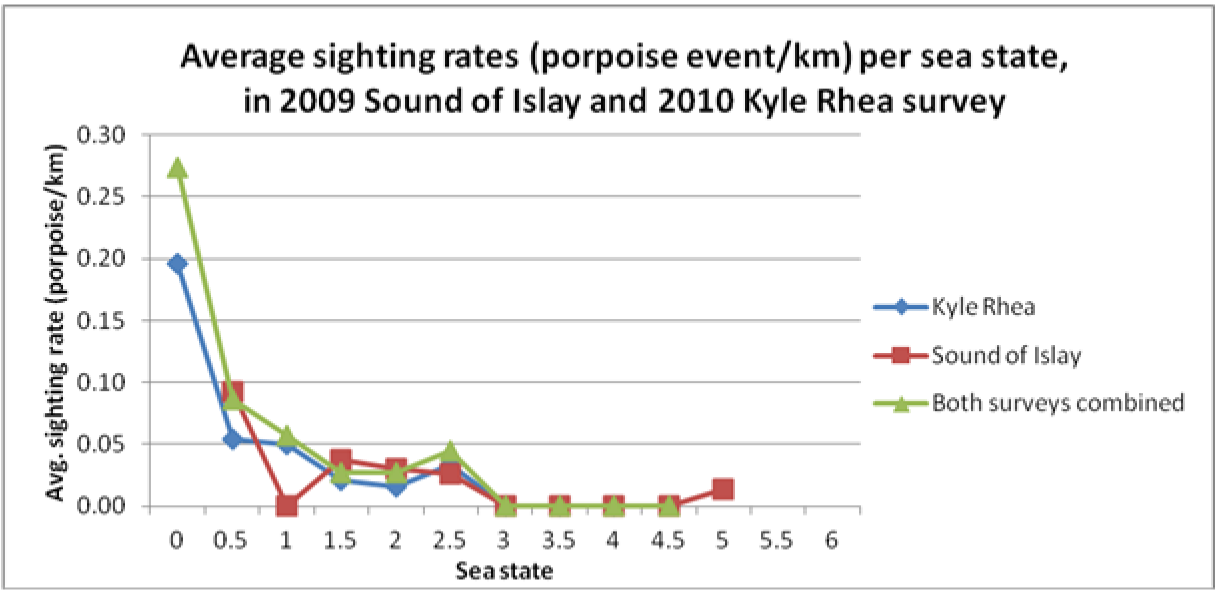

Figure 13. Average sighting rate (porpoises/km surveyed) at different sea states, for the 2009 Sound of Islay survey, the 2010 Kyle Rhea survey, and both surveys combined. Only Kyle Rhea data were available at sea state 0. There is an obvious decline in sightings beyond sea state 0.5.

The decline in sighting rates with increasing sea state implies that porpoises went undetected (by the visual observers) in rougher conditions. In order to estimate how many porpoises might have been missed, correction factors were calculated for each sea state from the above graph, by taking the ratio of the mean sightings rate at a particular sea state to the mean of sightings rate at sea state 0 (c_n), using the equation:

$$c_n = sr_n/sr_0$$

where sr_n is the mean sightings rate at sea state =n, and sr_0 is the mean sightings rate at sea state =0 (Evans & Hammond 2004). Porpoise sighting events (i.e. reports of at least 1 porpoise sighted) were multiplied by these correction factors to estimate how many such events might have been missed. If data from both surveys are combined, a total of **209** additional sighting events would have been detected if sea states had been 0 throughout.

When accounting for sea state, overall harbour porpoise sighting rates (#/km) were very similar between the two survey areas (0.04 km^{-1} in Sound of Islay, vs. 0.07 km^{-1} in Kyle Rhea). When looking at smaller spatial scales, the highest sighting rates (0.22 km^{-1} and 0.24 km^{-1}) occurred in the Sound of Sleat – Mull Approaches and South of the Sound of Islay, respectively (see Tables 5, 10). Both of these areas contain large expanses of deeper open water known to be favoured by porpoises at larger spatial scales (Booth 2010). While sightings did occur in both tidal-stream channels, they were much lower (1 – 2 orders of magnitude) than in the open waters to the south.

Because there is far less influence of sea conditions on the detectability of porpoises during the acoustic surveys the results from this method were less weather dependent. Instead acoustics methods have their own biases (ambient background noise which affects detectability is analogous to sea state and echolocation rate affects cue production and is comparable to surfacing rate) but the two methods together offer independent perspectives of spatial porpoise occurrence. Overall the two methods produced very similar results from both sites, namely that porpoises did occur in the tidal narrows but at much lower densities than in adjacent more open waters (in both cases to the south).

SECTION 2: USE OF NOVEL ACOUSTIC METHODS TO INVESTIGATE PORPOISE OCCURRENCE IN TIDAL-SITES

Odontocete cetaceans use echolocation to navigate and locate prey. The echolocation sounds of harbour porpoises are intense, specific in their frequency structure and emitted in characteristic bursts or trains. As a result it is possible to electronically pick out these underwater calls from background noise (with increasing levels of sophistication) automatically. The towed hydrophone in Section 1 was used to detect such calls from a boat moving in predefined transects. Here we assess three other techniques using this acoustic feature of harbour porpoises to investigate their (a) temporal occurrence, (b) spatial occurrence and (c) diving behaviour.

2.1 Temporal occurrence

A number of automatic porpoise click detectors have been developed in recent years with some being built into entirely autonomous systems. The only commercially available version of this technology is built by Chelonia Ltd and called PODs. Of these, the most recent version is the C-POD. This device uses digital waveform characteristics to detect odontocete clicks and logs the time, centre frequency, loudness, duration and bandwidth of each. Thus, in addition to porpoises they can also detect species such as bottlenose dolphins and killer whales and to a lesser extent successfully classify them. Other parameters are also recorded including orientation relative to vertical (*i.e*., the extent to which the device is deflected by the current), temperature, boat sonar occurrence and relative levels of background noise. C-PODs are housed in relatively small tubes (66 cm long, 4 kg in air) and have sufficient battery and memory capacity to remain submerged and operating for several months at a time (usually ~ 3 months).

C-PODs (and their previous version T-PODs) have been widely used to investigate porpoise occurrence and particularly temporal patterns for a wide range of studies ranging from porpoise ecology, to fishery interactions and more recently their occurrence in areas of interest to wind-farm construction (Scheidat et al., 2011). The deployment of these devices in tidal-stream areas to understand porpoise occurrence is therefore attractive. However, their utility in this environment has not been fully investigated. Of particular concern is whether it is possible to successfully moor the devices in an upright position and whether they can detect porpoises against the high levels of turbulence, sediment transport and general background noise typical of tidal-stream sites. To explore this issue, we attempted to moor C-PODs in the Sound of Islay in 2009 and around the Kyle Rhea in 2010.

2.1.1 PODs in the Sound of Islay

Moored C-PODs were deployed in the Sound of Islay in September 2009, in two locations. One POD (“POD 664”) was weighted with 3 kg of lead and chained (with Northern Lighthouse Board permissions) to an existing navigation buoy (Black Rock Buoy 55°47.5 N 6°04.0 W). It was suspended so that it would be three meters below the surface in water about 25 meters deep near to the middle of the Sound. The second (“POD 666”) was moored with ropes and mooring weights off the shore at the Carraig Mor lighthouse (55° 50.3 N 6° 4.1 W). This position was much closer inshore (150 m from the beach) but immediately adjacent to the site of interest to the tidal-stream industry. It was floated about two meters off the bottom in 10 m of water and given 10 kg of positive buoyancy using incompressible pellet floats. Both sites experienced the full tidal stream. Two episodes of deployment were tested. The first occurred in mid-September 2009 for three to five days and the second ran for longer from late September into the winter of 2009.

On recovery after the first deployment the PODs from both sites were clearly influenced by the currents (device tilt data). However the recorded patterns were different. The Carraig Mor POD (bottom, shore-line mounted) was not strongly influenced by currents, showing only moderate deviation (20-30º) from vertical and only on one direction of flow. In contrast, the Black Rock Buoy POD (surface, mid-channel mounted) was heavily influenced by currents both during ebb and flood flows. This was to the point where the POD was only rarely in the correct upright position and was frequently pushed to be near horizontal (see Figure 14).

High levels of ambient noise impact the ability of C-PODs to detect porpoise clicks. This occurs in two ways – firstly by masking the clicks and making them difficult for the software to detect and secondly by rapidly filling up the device's recording buffer with other non-cetacean click detections. The first effect is difficult to quantify but the second is easily measured because it truncates the fraction of each minute recorded. These "fractions of lost time" can be used as a rough measure of the ambient noise levels in the surrounding environment. The Carraig Mor POD 666 experienced only limited data loss in this manner, indicating that it was deployed in a relatively quiet environment and should not have missed porpoise echolocation events should they have occurred. In contrast the Black Rock Buoy POD lost much of its recording time due to excessive ambient noise. Overall in the first short deployment, no porpoise clicks were detected by either POD. However, both did detect dolphin click trains at various points during their deployment and coincidentally we observed bottlenose dolphins in the area during that week.

The longer-term deployment of PODs was less successful. When the Northern Lighthouse Board serviced the Black Rock Buoy in the winter, neither the POD nor its tethering chain was still present on the attachment point. We suspect either excessive wear from the near continuous flow had worn through the 5 mm chain and / or galvanic action between the metal buoy and chains had preferentially eroded our chain and the device had come loose. The Carraig Mor mooring fared no better and the tether rope was found to be chafed through and the POD missing. Since neither POD was retrieved no data could be recovered.

Overall, the Sound of Islay POD experience showed that tethering PODs in tidal waters is problematic, both from the practical perspective of keeping gear orientated correctly, and for long enough to be useful, but also from the point of the resulting porpoise detection data being limited by the levels of background noise. Mooring techniques can be improved but the background noise issue is particularly problematic because it scales with the tidal flow and the occurrence of porpoises during high flow periods is a key parameter of interest.

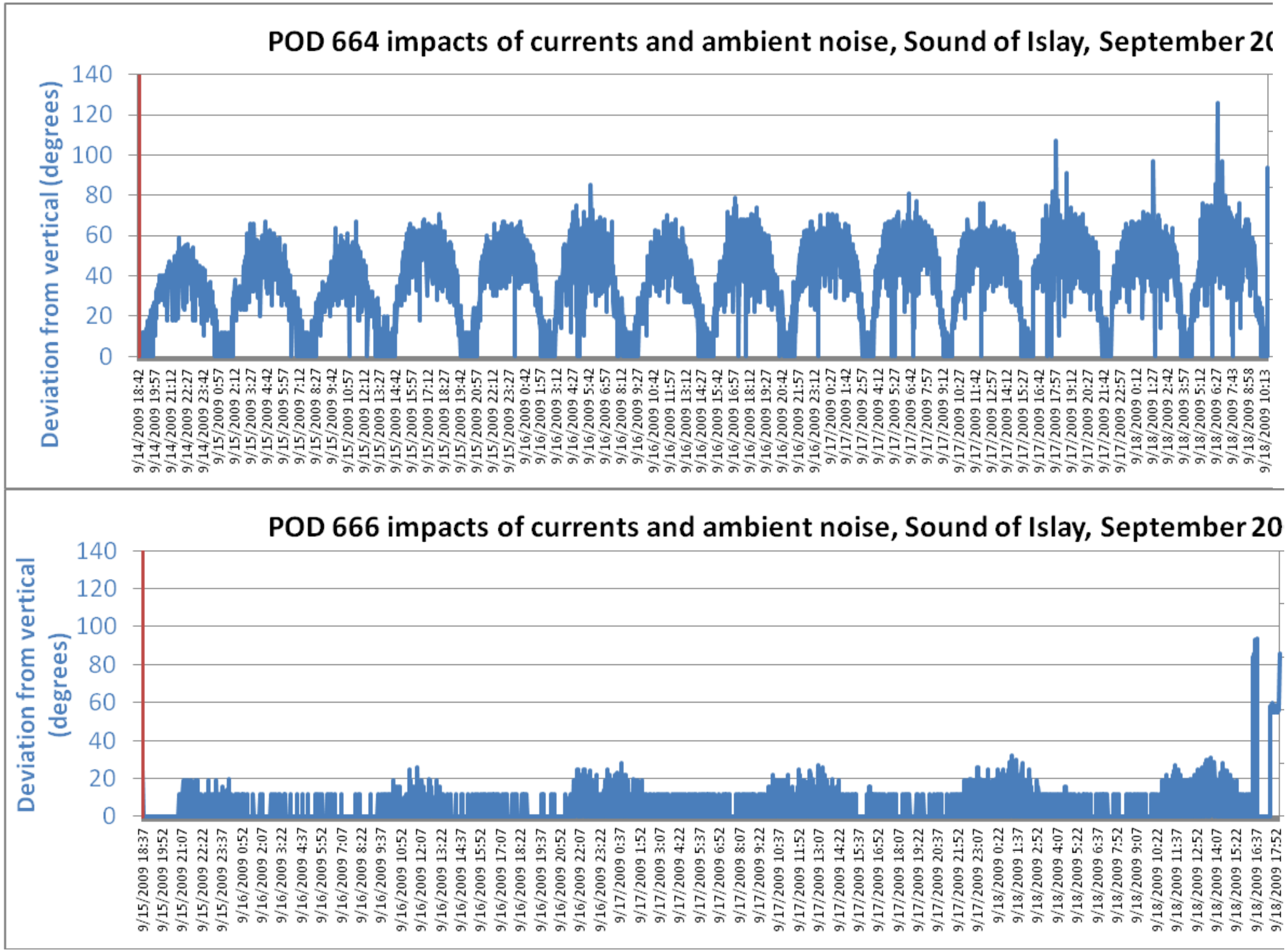

Figure 14. POD deviations from vertical in response to currents, Sound of Islay, September 2009. The cyclic nature of these deviations demonstrates the tilt resulting from the flow of water past the device.

2.1.2 PODs around the Kyle Rhea

Following the lessons learnt from the Sound of Islay POD work, a second trial was performed around the Kyle Rhea area coincident with the May 2010 visual and acoustic boat surveys (Section 1). One POD (#666) was moored in a non-tidal site 16 km from the Kyle Rhea (and acting as a control) near Tartar rock (57° 6.8 N 5° 48.7 W) on the Skye side of the southern Sound of Sleat. A second POD (#664) was deployed at the southern mouth of the Kyle Rhea in a site immediately next to (but out of) the main ebb flow (57° 13.4 N 5° 39.0 W). A third POD (#668) intended for other experiments was used opportunistically first in the entrance to Loch Duich to the North of the Kyle Rhea (57° 16.3 N 5° 31.5 W) and then in the Northern Sound of Sleat at the point where the full force of the ebbing tide from the Kyle Rhea meets the mainland shore (57°12.2 N 5° 38.7 W). All moorings were bottom mounted in 15-20m of water with vertical risers to surface floats and the PODs suspended 5 m off the bottom. Deployment durations ran from approximately 2 to 4.5 days.

The control POD in the non-tidal southern Sound of Sleet malfunctioned during deployment and did not record any data. In contrast the POD at the southern entrance to the Kyle Rhea functioned well and the on-board inclinometer indicated only moderate deviations from vertical (out to approx. 40º) roughly every 12 hours, during periods associated with flooding (north-going) tides (Fig 15). Noise levels did truncate some of the monitoring but showed no obvious relationship to tidal currents or time of day. Over its 4.5 day deployment it detected few porpoises. The automatic C-POD software logged five intense echolocation events (18-60 clicks per minute). All of these occurred between late evening and early morning around ebbing/low tide. No such click events were recorded during the equivalent tidal state during daytime. These events offered too small a sample size to draw conclusions so the detection data were manually examined to see if there were other likely porpoise events that fell below the software’s trigger threshold. Doing this revealed another four events. These also only occurred at night (Figure 15). While this evidence is not conclusive it does suggest that porpoise use of this area was both tidally and diely influenced.

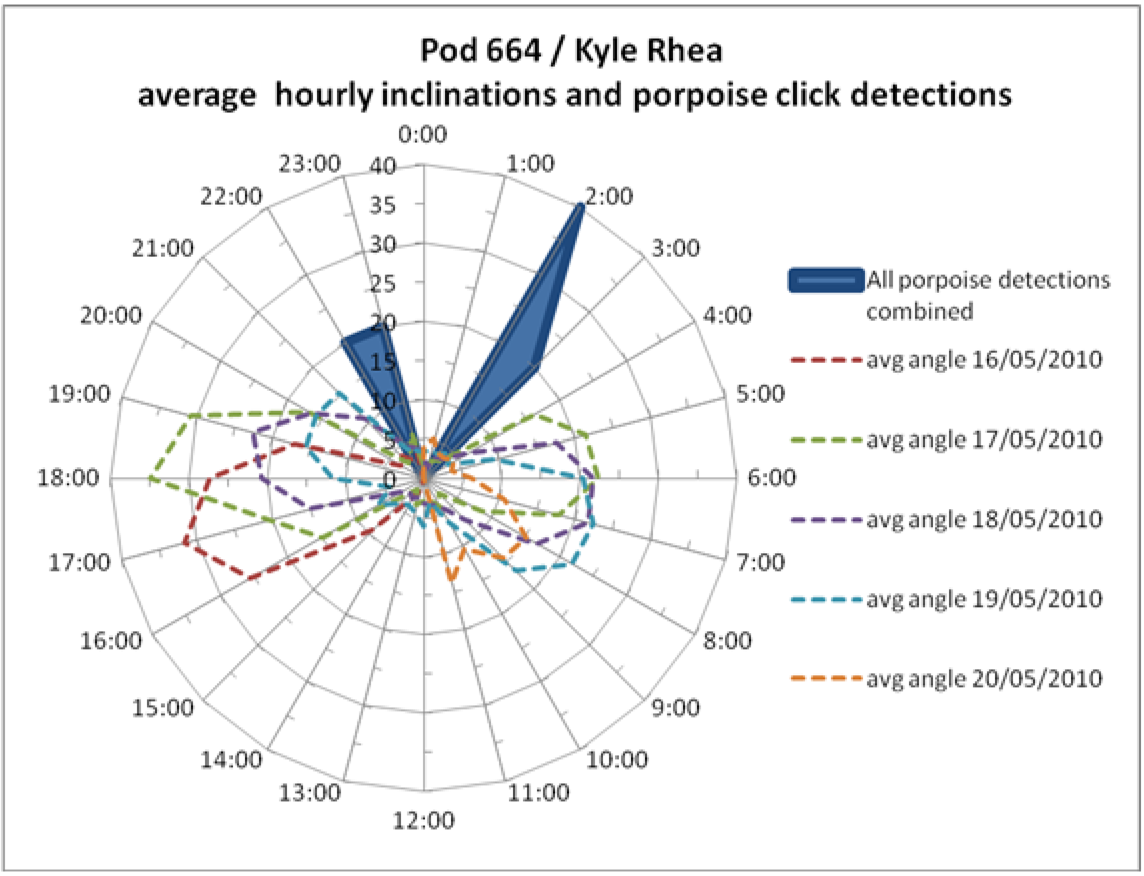

Figure 15. Relative distribution of porpoise clicks and average hourly deviations from 0º (vertical orientation) recorded by C-POD 664, moored at the southern entrance to Kyle Rhea from 16-20/05/2010.

The opportunistic POD was initially deployed for half a day in Loch Duich during the testing of the vertical hydrophone array (see Section 2.3), then for two days next to the boat's overnight anchoring position at the mouth of Loch Duich and then finally for two days in the northern Sound of Sleat. Comparatively low levels of noise were recorded during the deployment, particularly in the Sound of Sleat North area. In contrast to the C-POD at the southern entrance to Kyle Rhea this one detected frequent porpoise clicks (between 7-111 clicks/minute) at all locations with no obvious correlation between tidal or daylight cycles with porpoises apparently present in these areas at all times (Figure 16). Particularly interesting is the comparison of the detections in the northern Sound of Sleat. Despite the recorders being less than 3 km apart, one (immediately next to Kyle Rhea) recorded porpoises only at very specific times while the other logged them throughout the deployment. Both sites were very strongly influenced by the tidal flow.

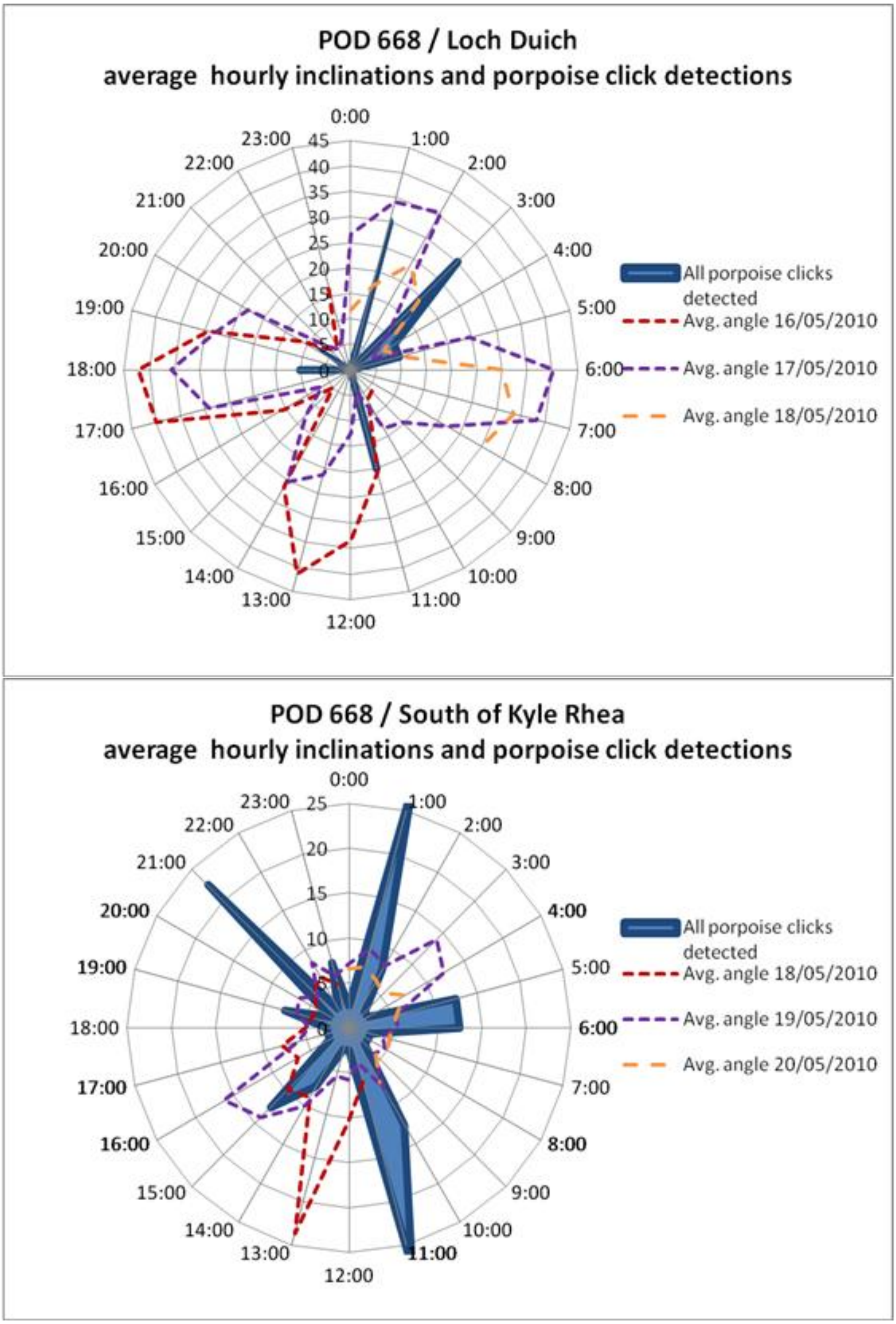

Figure 16. Relative distribution of porpoise clicks and average hourly deviations from 0º (vertical orientation) recorded by A) POD 668, moored in Loch Duich from 16-17/05/2010, and B) POD 668, moored in the Sound of Sleat North from 18-20/05/2010, over 24-hour periods.

2.1.3 Lessons learnt from mooring PODs in tidal sites

PODs have proved useful and informative (with caveats) for studying porpoise occurrence in a wide variety of locations at sea. Accordingly, these devices are potentially very useful for monitoring tidal sites. However, these locations present specific challenges that cannot be overlooked. The main four are outlined below.

First it is technically difficult to moor PODs correctly in fast flowing water. The flow-induced drag on any equipment means that substantial anchoring is needed to secure the devices to the seabed and with rocky substrate being typical heavy chain or blocks are needed rather than (lighter) sediment gripping anchors. Heavier gear requires larger boats for deployment and retrieval. The drag on any ropes also means that surface floats for location and retrieval may spend very little time actually at the surface. In tidal-stream sites it is very likely that floats (other than very large ones) will be dragged underwater on both flood and ebb tides. Once the surface float is submerged, the (now snaking) bottom to surface line then runs the risk of snagging on the seabed and so not allowing the buoy to return to the surface on slack tide. Incompressible floats are also needed to ensure they retain their buoyancy once submerged. With “surface” gear being dragged under when the tide runs the time windows for device recovery become very short. For example the tidal flow that was “slack” enough for our buoys to surface in the Sound of Islay at springs was in the region of six minutes. Servicing multiple devices then becomes problematic.

The second substantial issue is wedded to the difficulties of keeping bottom to surface lines vertical (see above). This is the problem of simultaneously keeping the PODs themselves vertical and up in the water column. While their default setting of PODs is to turn themselves off once they fall horizontal this can be turned off. However, the detection capabilities of knocked-down PODs are likely to be different to correctly deployed ones. This is likely to bias any temporal comparison of porpoise occurrence in tidal sites.

Thirdly, with heavy anchoring equipment combined with near-continuous water motion all the way to the seabed leads to substantial wear on the mooring tackle itself. We experienced rope and chain chaffing through on our two longer term deployments with the resulting total loss of both the equipment and the data. Mooring loss is relatively common for scientific equipment and without recovery the reason for this usually remains unresolved. Removal through fishery interactions is likely for many sites but rapid gear failure is an expected additional issue in tidal sites.

The three issues outlined above are all technical and are likely to be resolved in the coming years with sufficient effort, resources and experimentation. A final one is more challenging because it is an inherent aspect of the acoustics of these sites themselves – namely that as the tide flows, the broad spectrum background noise increases massively so that it can overload the click detection capabilities of the POD and also mask the porpoise calls themselves. Because background noise varies with tidal flow it then becomes difficult, or impossible, to truly relate porpoise occurrence to tidal flow conditions. No direct fix for this is obvious other than careful site selection based on ambient background noise. It must also be remembered that this background noise may influence the porpoises directly as their echolocation requires the successful reception of the low-level echoes returning from their outgoing clicks. The resilience of their echolocation to high levels of background noise is little known but it has been suggested that porpoises either leave such areas during times of high background noise or, more problematic here, cease echolocating.

Given these issues, the results from our trials (Kyle Rhea in particular) showed that porpoises can be detected with careful device placement and that patterns of detection may vary at relatively fine spatial scales. Thus multiple simultaneous deployments are likely to be required to properly understand how animals use these areas.

Finally, in the Sound of Islay deployment we detected dolphins on several occasions and indeed saw bottlenose dolphins in the area whilst waiting for buoys to surface at slack tide. Such POD deployments are therefore informative for other species as well as harbour porpoises so long as direct observations can ground truth the actual species beyond simply “dolphins” as identified by the current C-POD software.

2.2 Spatial occurrence

The section above (2.1) demonstrated several problems with deploying fixed recorders in tidal streams, however the detection and logging capabilities of PODs remain highly attractive in studying porpoise occurrence. Likewise the use of a boat to survey an area and detect porpoises either visually or acoustically offers clear perspectives on likely habitat use at scales relevant to the tidal-energy sites. Boat surveys are however labour intensive and expensive which together typically results in relatively short time windows being available to study animal occurrence. Here we explore the possibility of combining the benefits of these two approaches along with a key property of tidal sites (vigorous flow) to develop a new method to study porpoise spatial distribution. For this we took standard C-PODs but freed them of their moorings and instead attached them to a drogue designed with surface floatation and position fixing capabilities. We then released this equipment upstream of the site of interest and let it flow with the tide over the area before retrieving it. Porpoise detections recorded on these “Drifting PODs” could then be mapped. (The method is more fully described in Wilson *et al*., In Press).

To build a Drifting POD, we took the standard C-POD and tethered it to a weighted coastal-water drogue which was itself attached to a dan-buoy fitted with GPS recorder and high visibility flag (Figure 17). The POD was mounted so that it was vertical 5 m below the surface. To test the concept we used a RIB to release a pair of these drifters into the Kyle Rhea tidal stream simultaneous to running the visual and acoustic boat surveys in May 2010 (see Section 1). The location data logged on the GPS recorders were then matched to POD data on a minute-by-minute scale.

These tests were performed 23 times (14 on May 18th, and 9 on May 20th, 2010) on both flooding and ebbing tide. Figure 18 shows the spatial distribution of these drifts and since the units recorded a location once a minute the spacing of the dots in each track gives a visual indication of drift rate. On May 18 both PODs were released 7 times in succession within the Kyle Rhea Central Channel on the falling tide. Once released the devices made rapid progress with the tide down and into the northern Sound of Sleat before being retrieved and reset. The average deployment time was 29 minutes (SD of 12 minutes) during which the PODs travelled, on average, 2.0 km downstream (SD = 0.9 km) before being retrieved. Calculated on a minute-by-minute basis, these C-PODs attained an average speed of 1.1 $m.s^{-1}$ over the ground (SD=0.4 $m.s^{-1}$), or around 4 $km.hr^{-1}$. On May 20, 4 releases took place at the southern entrance of Kyle Rhea (on the northerly flood tide), one from the middle of the Central Channel (around high tide) while the remaining 4 releases occurred at the northern entrance (on a southerly tidal flow). Average deployment time here was 66 minutes (SD = 24 minutes), during which the PODs travelled, on average, 3.2 km (SD = 0.8 km). During these deployments, the PODs travelled at an average speed of 0.9 $m.s^{-1}$ (SD = 0.4 $m.s^{-1}$). Drifting speeds of up to 3.2 $m.s^{-1}$ and as low as 0.03 $m.s^{-1}$ were recorded during the course of these deployments.

In terms of tidal coverage overall, two deployments (of the drifter pairs) occurred within an hour before high tide (moderate northward flow) and a single deployment occurred immediately after high tide (slack water). All other deployments occurred as tides were falling until approximately 30min before low tide (strong to moderate southern flow). Highest speeds (>2 $m.s^{-1}$) were encountered in 2 areas: in the middle of the Central Channel just north from its narrowest section where water flowing southward gets compressed and slowed down, and from that narrowest section southward to the uppermost parts of Sound of Sleat North, where most PODs were swept out of the Central Channel of Kyle Rhea by a strong jet feature of the tidal current. This jet feature, as indicated by the PODs' travelling speeds, did not extend much beyond the 50m isobath of the Sound of Sleat North (see Figure18). Conversely, some of the lowest speeds (<0.5m/s) were encountered in the middle of the Central Channel, where PODs were sometimes captured in eddies or peripheral surface currents and returned in the direction from which they had originally come.

Processing of the data held by the PODs revealed that they did record porpoise click trains (25-61 $clicks.min^{-1}$). All of these were detected on deployments on the May 18 ebb tide tracks and all of these detections occurred once the drifters had left the Kyle Rhea proper and had entered the deeper waters of the Sound of Sleat North area (black stars Figure 18). This was the area that the survey boat *Silurian* also visually and acoustically detected the majority of its porpoises in the greater Kyle Rhea area. The drifters recorded no porpoises in the Kyle Rhea channel itself. It must be noted that because the drifters moved with the current, multiple detections of porpoises on the same drift were not necessarily independent. This feature distinguishes the drifting acoustic method from the powered boat-towed method which wouldn't suffer from this bias.

In addition to porpoises, the *Drifting PODs* also encountered high levels of ambient noise. When severe, these sound quickly filled up the devices' one-minute buffer. We were able to investigate the occurrence of this background noise by plotting it as fractions of each minute truncated by the buffer saturating. Noise levels were low (0-20% of each minute lost) during most of the deployments, but reached high levels (>40% lost) in particular areas (see Figure 19). These high levels of ambient noise were confined to the narrowest section of the Central Channel when the tide was in mid-flow. Noise levels rapidly fell as the tide slowed. A comparison of these results indicates that a zone of significant ambient noise is created locally within the Central Channel of Kyle Rhea during at least the falling tide, within which the ability of PODs to record cetacean vocalisations is severely curtailed. This area is one of the places where current speed was greatest; however, PODs subjected to comparable current speeds south of the Central Channel suffered far less interference. More importantly, as the PODs are passively drifting with the current, water movements past the acoustic sensors cannot be responsible for this noise. Because the ambient noise was relatively restricted in space and time, the levels experienced would most likely have allowed the detection of harbour porpoise clicks along most of the drifters' transects.

The *Drifting POD* trial appeared to be successful. We were not only able to survey a relatively large area using just two devices, two people, a small boat in only two days but we found a similar (albeit less detailed) result than the much more intensive and costly boat surveys[2]. In addition, the drifts revealed spatial and temporal structuring in background noise. Crucially this was noise that limited the abilities of the PODs to record echolocation sounds. Thus we were able to rapidly provide data that would inform the appropriate placement of moored PODs in future.

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[2] Note: A second run of drifters was performed in 2011 and provided much more spatial resolution on porpoise occurrence – see Appendix 2. Because this survey was funded using other resources the results were not included in the main body of this report.

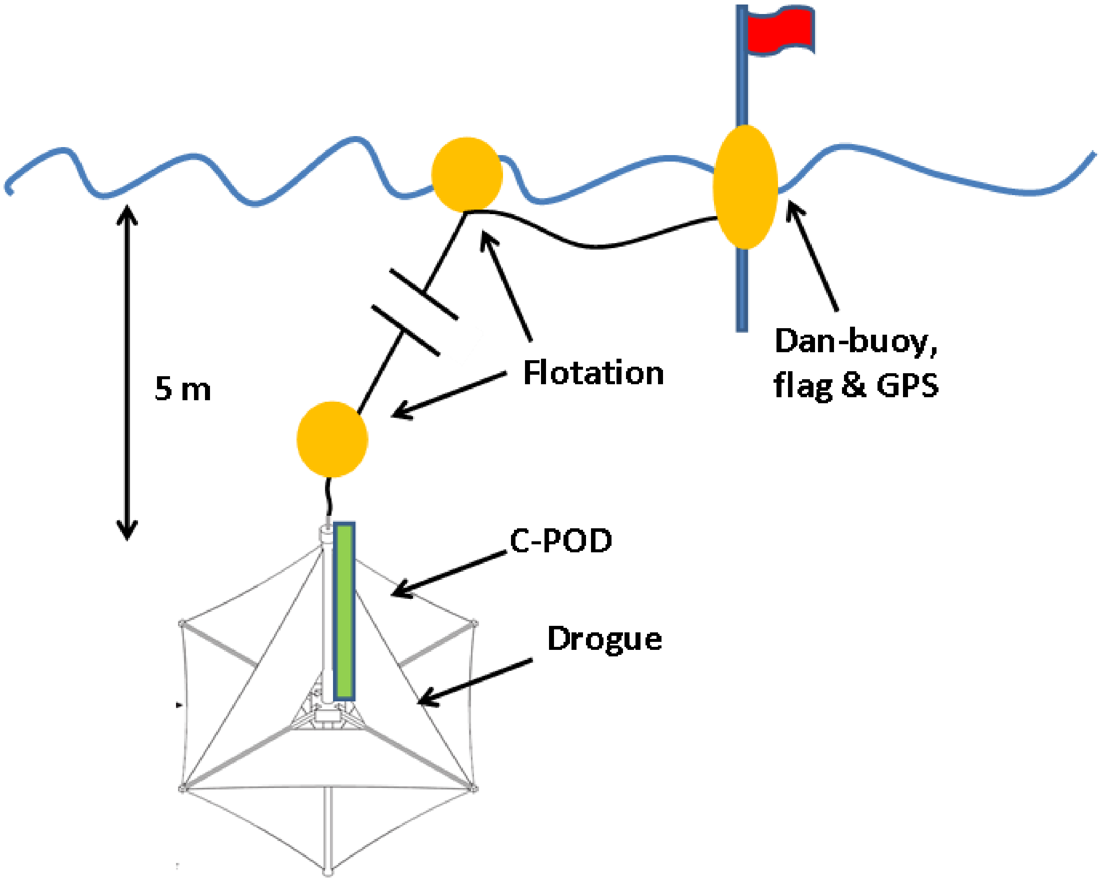

Figure 17. Schematic of the components of the *Drifting POD* equipment. The ropes and flotation was designed so that the hydrophone in the POD was suspended 5 meters below the surface.

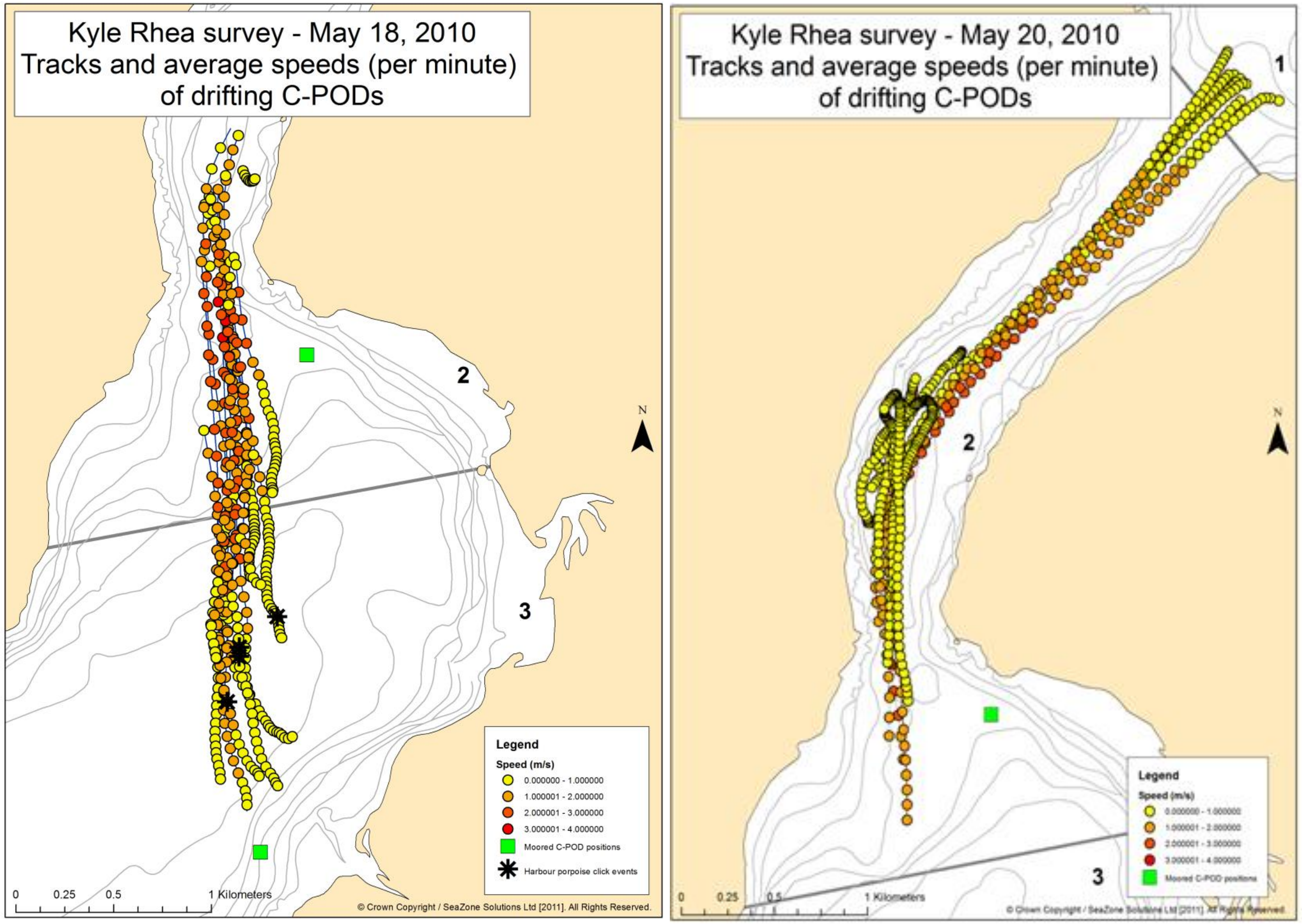

Figure 18. Trajectories followed, and flow speeds experienced, by consecutive deployments of drifting C-PODs in Kyle Rhea (1-minute averages) during May 18 and 20, 2010. All deployments on May 18 were southward-flowing, while there was a mixture on May 20 (see text). Note that highest flow speeds were concentrated in two areas on either side of the narrowest section of the Central Channel of Kyle Rhea. Locations of porpoise click event detections and moored C-PODs are indicated.

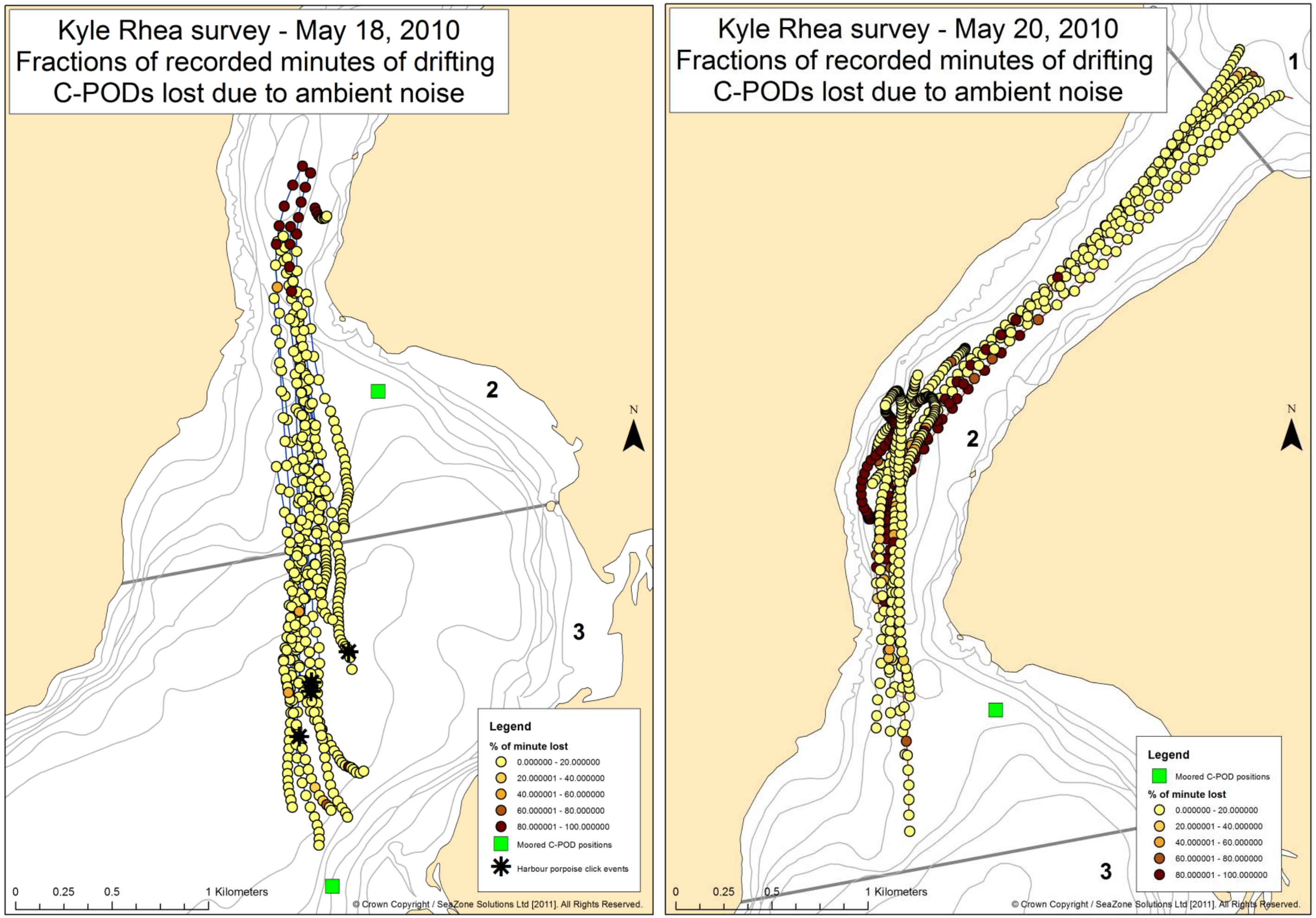

Figure 19. Ambient noise levels recorded during consecutive deployments of drifting C-PODs in Kyle Rhea (1-minute averages) during May 18 and 20, 2010. Loudest ambient noise levels (>80% of each minute in recording time lost) occurred in a comparatively localised area north of the narrowest section of the Central Channel. Locations of porpoise click event detections and moored C-PODs are indicated.

2.3 Diving behaviour

The underwater behaviour of porpoises at tidal energy sites, and in particular the proportion of time they spend at different depths, is highly relevant to any realistic assessment of collision risk. Because tidal narrows are such physically unusual habitats we can't expect animals to behave within them in the same way as they have been documented to do elsewhere. Thus, extrapolation from dive behaviour recorded in other locations is not possible and instead, diving behaviour must be measured somehow in tidal areas during periods of high current flow.

Studies to investigate porpoise diving behaviour have primarily targeted the use of telemetry tags attached to free swimming porpoises. These are currently unsuitable for looking at porpoise behaviour relative to tidal turbine collision risks, because there is no guarantee that a porpoise once tagged will spend any time near a habitat of this type and also opportunities to tag porpoises in the UK are virtually non-existent. Alternative methods using Sonars show some promise but have not yet been successful and are likely to be range limited for this application.

Instead, the possibility of using triangulation of the calls of free-ranging porpoise to determine their depth using arrays of hydrophones has been suggested. However, typical methods of using arrays for spaced hydrophones are inappropriate in tidal areas because of the difficulties of keeping appropriately orientated while in the flow. Accordingly, in 2009, as part of a study funded by the Welsh Assembly Government Ecologic UK Ltd and SMRU developed a vertical hydrophone array and a methodology for locating porpoises and measuring their depths using passive acoustics (Gordon et al., 2011). Using a string of hydrophones (vertical array) suspended directly below a passively drifting boat means that the vessel and array can drift through a tidal area without the inherent dangers of trying to anchor or counter the flow. Additional work on analysing vertical array data using Markov Chain Monte Carlo localisation was undertaken by Macaulay during his Bachelors thesis. As part of this current project the Ecologic array was loaned to SAMS and was deployed from the HWDT research vessel *Silurian*. A variety of recordings of real porpoises in still waters and high tidal current areas were made and trials with test sound sources at known ranges and depths were undertaken. On the current project there was insufficient time to collect enough data to be able to make definitive statements about porpoise behaviour, however, it did serve as a trial and proof of concept as well as providing the first indications of porpoise underwater behaviour in strong tidal current areas off the West Coast of Scotland.

The vertical array consisted of 4 individual hydrophone elements (in two pairs 25 cm and 15 m apart) mounted on a heavily weighted (100 kg) line hung straight down under the drifting vessel (Figure 20) The orientation of the line relative to vertical was monitored using two inclinometers. The output from the hydrophones was amplified and digitized (at 500 kHz) and recorded onto a hard drive for later analysis. That analysis made use of the difference in arrival times of individual echolocation clicks at each of the spaced hydrophones. These time differences were entered into a Markov Chain Monte Carlo Algorithm which statistically examined the potential source locations of the received sounds and calculated a cloud of points representing a probability distribution of depths and distances for the vocalising porpoise. Because the array was effectively one dimensional, it was not possible to determine a specific lateral bearing to the vocalising porpoise.

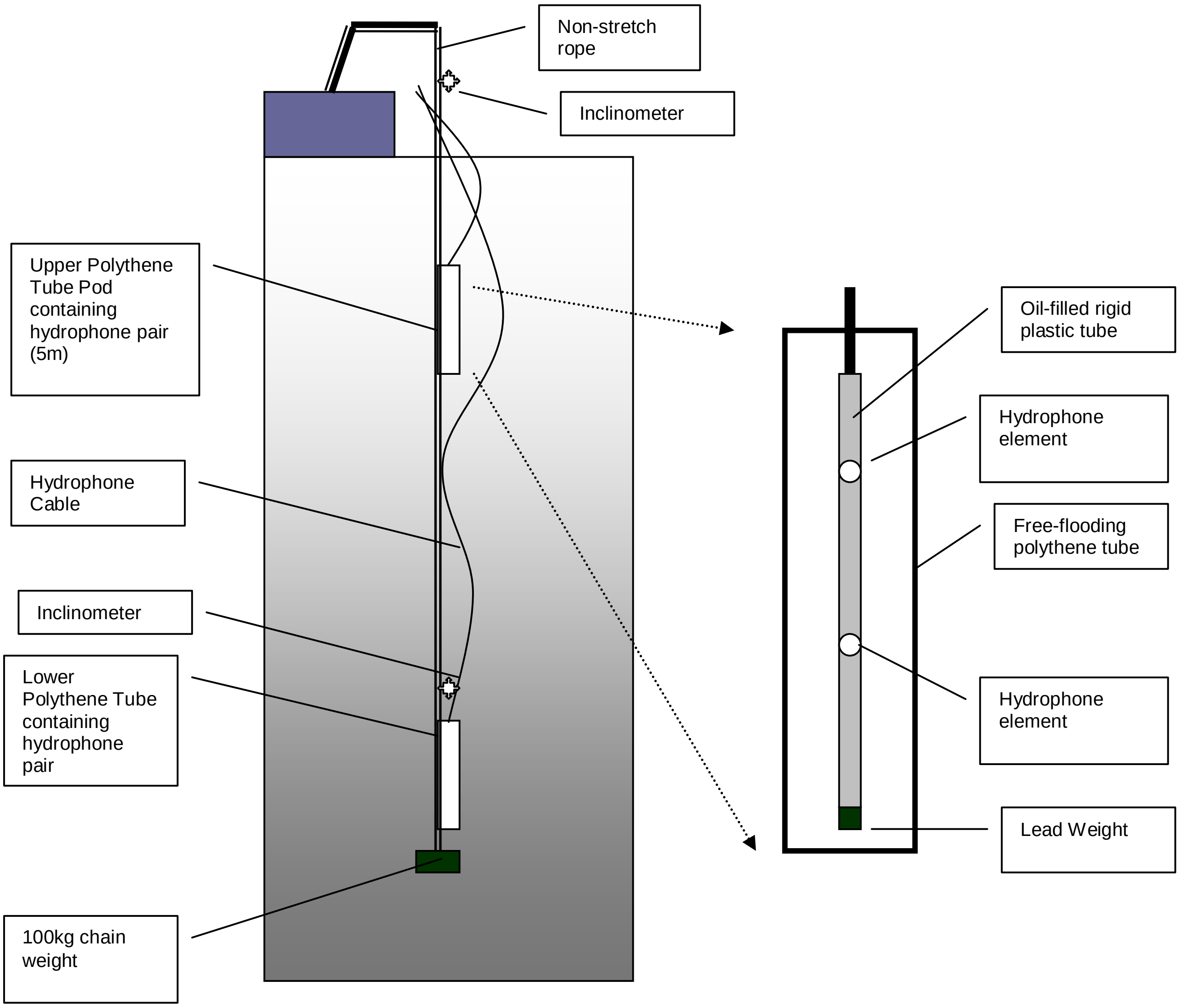

Figure 20. Four element vertical hydrophone boat-mounted array used for determining depth of porpoise vocalisations.

A number of trials were performed in the Kyle Rhea area in May 2011 alongside the surveys outlined in Section 1. These consisted of a calibration experiment with a porpoise-like sound source being moved over a range of depths and distances from the array. An examination of the impact of inclination error was also performed. In addition the array was used to record real porpoise echolocation in two locations. The first was in the relatively still water of Loch Duich and the second was in the tidally influenced northern Sound of Sleat on the ebb tide where a vigorous jet of water crosses the Sound from north-west to south-east. Both of these sites are in relatively deep water extending from 50 to at least 100 m.

The calibration trial showed that it was possible to accurately determine both distance and depth of received porpoise-like clicks out to a range of at least 127 m and depths below 5 m. Over one thousand real porpoise echolocation clicks were then localised in Loch Duich and the northern Sound of Sleat. Overall the depth of these clicks was surprisingly shallow in comparison to both the likely depth of water these sounds were made in (50 – 100 m) and also relative to porpoises studied elsewhere. The mean depth of the clicks detected was just over 10 m deep with a maximum of around 28 m (Figure 21). By linking successive clicks together it was also possible to part-reconstruct individual porpoise dive profiles and dives of between 90 and 120 seconds duration were observed.

This study was set up to test a developing method in a west of Scotland tidal-energy site. It proved successful in showing that the diving behaviour of free-swimming porpoises in tidal areas could be documented to a relatively high degree of accuracy and revealed unexpected shallow diving behaviour in relatively deep water. Of course this method has caveats, most notably that it only works for vocalising animals, but it offers a very practical way to investigate porpoise behaviour in areas of direct interest to the tidal-energy sector and also at all states of the tide.

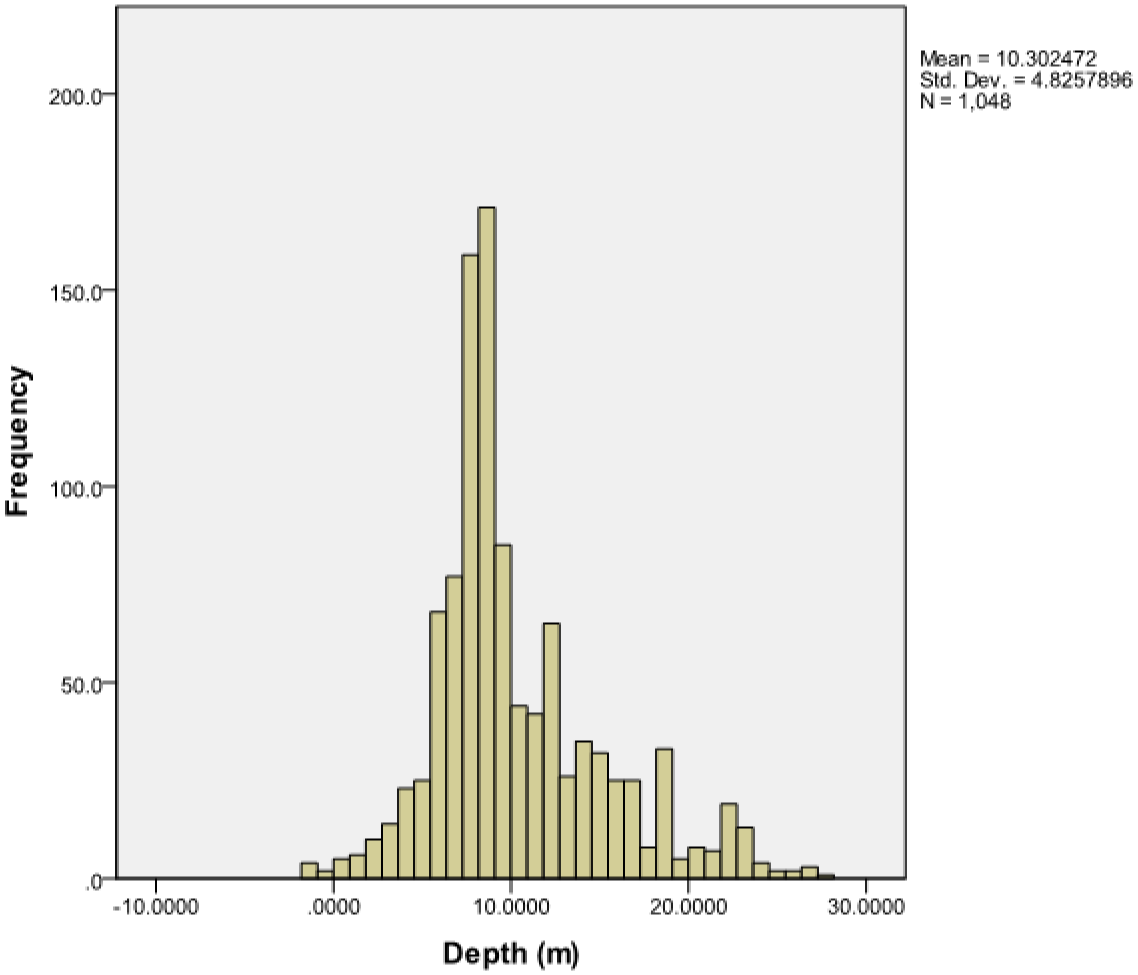

Figure 21. Histogram of acoustically derived depths for all acoustic porpoise encounters.

SECTION 3: OVERALL DISCUSSION AND IMPLICATIONS FOR COLLISION MODELLING

1.1 Key findings

1. We set out to visually and acoustically survey the Sound of Islay and the Kyle Rhea and surrounding waters for harbour porpoises in the summers of 2009 and 2010. To allow comparison, we used a research boat (HWDT's *Silurian*) that has surveyed much of the rest of western Scottish waters for cetaceans over the preceding decade. However, using a survey vessel that cruises at speeds only marginally faster than the high energy tidal flows in the two tidal narrows presented the possibility of significant survey bias for both visual and acoustic recording methods. To resolve this, we adapted the trajectory of the conventional survey path with respect to the flow so that the boat crabbed across the flow at a rate equivalent to progress over the bottom. We tested this new method and successfully applied it to the Sound of Islay and Kyle Rhea. Survey effort was conducted for a total of 16 days and covered over 1300 km of sea.

2. Harbour porpoises were seen and acoustically detected in all areas surveyed. Of particular focus for this study were the areas of strongest tidal flow in the Sound of Islay and the Kyle Rhea because of the interest in these for commercial tidal stream arrays. Porpoises were seen and acoustically detected in both of these sites. However, rates of sightings or detections were an order of magnitude lower than surrounding waters, particularly the Sound of Jura and northern Sound of Sleat. For example, sightings in the Kyle Rhea narrows were around 0.01 km^{-1} whereas to the south in the Sound of Sleat: they ranged from 0.09 – 0.22 km^{-1}. As with other studies, porpoise sightings were heavily influenced by sea conditions but this effect did not explain the low sightings rates in the tidal narrows because these areas, due to restricted fetch, were some of the calmest surveyed during this study (Tables 5 and 10). Acoustic detections showed a similar pattern with 0.2 click events.km-1 in the narrows and 5.41.km^{-1} in the open water to the south. Rates in the Sound of Islay were similar (sightings in narrows 0.01 km^{-1} vs. 0.08/km and 0.24/km to the south; acoustic detections 0.02 click events.km^{-1} versus 0.09 click events.km^{-1}).

3. Other than demonstrating that porpoises use these areas and occur at lower densities than in adjacent waters it was not possible during the boat surveys to determine their activity (foraging, transiting etc.) while in these highly tidal areas. Nevertheless this finding considerably strengthens suggestions of low use of tidal sites derived from more wide-scale surveys on the west of Scotland (Embling et al., 2010 and Booth 2010) and contrasts markedly with observations of porpoises targeting tidal-steam sites in Wales (Pierpoint 2008).

4. Other marine mammal species were seen on the surveys. Of particular interest were the sightings in the potential tidal-energy areas. Most abundant were harbour and grey seals which were seen in high numbers both in the

water and hauled-out in these locations. Both species were also seen in more open waters but at much lower rates. A minke whale, bottlenose dolphins and an otter were also observed in the tidal narrows. No basking sharks were seen.

5. In terms of cetaceans, these survey results indicate that porpoises (as well as other, less frequently encountered cetaceans) do not appear extremely abundant within tidal races in Kyle Rhea and the Sound of Islay, but do occur in them and especially in their close vicinity. It must be remembered that abundance does not equal importance because these areas are likely to be required for transit between other water masses. Bottlenose dolphins may be an exception because their abundance on the whole west of Scotland (Thompson et al., 2011) is very low so observing them in one of these narrows was both unlikely and potentially significant.

6. The use of moored acoustic porpoise detectors (C-PODs) proved problematic both from the practical perspective of keeping them moored but also because they experienced high levels of noise that substantially reduced their detection capabilities when the tide was running. Deployments out of (but adjacent to strong flows) could be used to detect porpoises in the neighbouring tidal-streams and provide useful information on temporal patterns. Wide variations in temporal occurrences detected using PODs sited relatively close to one another suggested that multiple detectors in a variety of locations would be best to characterise porpoise use of even relatively small sites. In addition other methods such as visual observations should be used to validate these findings.

7. We also explored the use of C-PODs allowed to drift freely in the current as part of a location logging drogue system. These proved highly successful and rapidly revealed similar patterns of porpoise distribution to the more intensive boat based surveys. That said, because these devices drift with the current, interpretation of the resulting data requires more careful interpretation than towed acoustic methods. In addition to mapping porpoise detections the drifters also revealed spatial patterns in the distribution of the problematic ambient noise experienced by the moored PODs. It may therefore be possible to use this method to explore for areas most suitable longer term device moorings.

8. Finally, we tested a new acoustic array-based method to determine the depth of echolocating porpoises (Gordon et al., 2011). The advantage of this method is that it can be deployed from a drifting boat in flowing water and is therefore workable in tidal-energy sites where other methods would not be. The array was deployed in the relatively still waters of Loch Duich and then in the moving water in the northern Sound of Sleat. The method proved successful and porpoises were both detected and their diving depths resolved. Overall, the depth of origin of more than a thousand clicks were determined. Although this was a test of the method rather than a definitive trial, the dive depths of porpoises were surprisingly shallow for this species (mean call detection depth 10 m, maximum 28 m) despite the recordings being made in water than was between 50 and 100 metres deep. This

suggests that diving behaviour data collected from other habitats may not be directly applicable to tidal energy sites such as the Kyle Rhea.

3.2 Implications for collision modelling

The encounter model developed for the Scottish wet renewables Strategic Environmental Assessment (Wilson et al., 2007) aimed to look at how frequently harbour porpoises would share the same time and space as operating tidal turbines. Given that we know that porpoises are likely to respond to turbines in some way, this was not a collision model but rather an opportunity to examine how often animals and machinery might encounter one another. Based on a number of assumptions, this model found that around 13 porpoises would encounter an operating turbine each year at close range unless it took avoiding or evasive action. Without other information of habitat preference then available, the model assumed that porpoise density in tidal-stream energy sites off western Scotland was equivalent to the density in the rest of their habitat. This present study was set up to test this equivalent-density assumption.

In both sites investigated, we found that porpoises were around an order of magnitude less abundant than surrounding waters. Furthermore because we used the same survey platform (Hebridean Whale and Dolphin Trust's *Silurian*) as used for other surveys on the west coast of Scotland it was then possible to compare our results with those over a much wider area equivalent to the SCANS survey block whose density was used in the original modeling study.

Combining all survey data between 2003 and 2010, observers on the *Silurian* sighted porpoises at a rate of between 0.039 - 0.058 porpoises.km^{-1}. This rate was strikingly similar to the sighting rate found for all of the areas surveyed in this study combined (0.04 - 0.07 porpoises.km^{-1}, SD 0.25-0.27). Thus when all of our survey effort was combined then it was broadly typical of the west of Scotland (i.e. from the Kintyre Peninsula north to Cape Wrath and west to St. Kilda including the Minch, inner and outer Hebrides). However, our sighting rates in the tidal narrows (both areas: 0.01 porpoises.km^{-1}, SD 0.10-0.19) were substantially less (an order of magnitude) than our most abundant areas and crucially an average or around five and a half times less than the average rate. If we are to add this to our encounter model then the rate of potential interaction falls substantially from 13 to around 1.8 to 3.25 porpoise-turbine "encounters" per year. However it must be emphasized that this number is not a collision rate, it is simply a rough indication of how often porpoises would encounter turbine blades if they took no action to approach or avoid them. Nevertheless this study suggests that, for the two sites at least, porpoise-turbine interactions are likely to be substantially rarer than if turbines had been deployed in other habitats.

Likewise, our preliminary investigations of porpoise vertical distribution using the suspended array suggested that the animals tended to use the upper layers of the water column in tidal areas. Accordingly, it is possible that these animals may encounter mid-water turbines less than otherwise expected. That said our investigations using the vertical array were mostly in waters adjacent to but not directly in key areas of interest to tidal stream developers. This is ironically because we couldn't find sufficient porpoises in fast flowing water for the method evaluation.

1.2 Implications for tidal-stream energy developments

1. Studying porpoises in moving water using conventional techniques is challenging and throughout this study we have had to substantially modify existing and develop new methods to gather useful data. Accordingly, it is very likely that the same will apply to monitoring around active turbines in these Scottish sites or elsewhere.

2. The low rates of porpoise detection in the two tidal-sites investigated means that potential rates of interaction between porpoises and tidal energy devices are likely much lower than would be experienced if these devices were sited elsewhere. That said, these sites are likely to be used as transit routes for animals living in waters either side of the narrows. Accordingly the day to day rate of interaction may be low but that is not to say that the number of individuals potentially passing through the area will be any lower than for more open water areas. Accordingly the opportunity for individuals to become familiar (learn, habituate etc) with both the site and the device(s) may be less.

3. The very low abundance of porpoises in the key sites of interest made it difficult to look in more detail at their behaviour in areas or fast moving water. In fact, this lack of sightings prompted us to cancel our plans for shore based observatory in favour of mobile acoustic methods. As a result it was impossible to determine what the animals' activities were in these sites (active foraging, simple transit etc). Accordingly, such low sightings rates will make monitoring of interactions between porpoises and tidal turbines difficult simply because of the low abundance creating low statistical power to detect patterns.

4. The profound differences in porpoise occurrence observed between these Scottish sites and the Welsh observations, in concert with 1) the suggestion of different temporal patterns of porpoise occurrence from PODs close to each other and 2) the surprisingly shallow dive depths documented, suggest that general patterns of porpoise ecology may not be easily applied to tidal-energy sites. It is clear that our understanding of this species in moving water needs further targeted study for generalities to be better established for this species. This is particularly true for tidal-energy developments in more open habitats such as waters to the west of Islay or Pentland Firth where studies such as those described here have not been performed but the eventual commercial scale developments are likely to take place.

Acknowledgements

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Appendix 1: Vertical Array Acoustic Monitoring of Porpoises in Loch Duich and Sound of Sleat as part of a Scottish Government Funded Project

Jamie Macaulay & Jonathan Gordon - *EcologicUK Ltd*.

Introduction

The underwater behaviour of small cetaceans at tidal turbine sites, and in particular the proportion of time they spend at different depths, is highly relevant to any realistic assessment of collision risk. Because tidal rapids are such physically unusual habitats we can't expect animals to behave within them in the same way as they have been observed to do elsewhere. Thus, there is no case of extrapolation using dive behaviour recorded in other locations. Underwater behaviour must be measured in tidal rapids during periods of high tidal current.

In 2009, as part of a study funded by the Welsh Assembly Government Ecologic Ltd and SMRU developed a vertical hydrophone array and a methodology for locating porpoises and measuring their depths using passive acoustics (Gordon et al., 2011). Additional work on analysing vertical array data using Markov Chain Monte Carlo localisation was undertaken by Macaulay as part of his undergraduate thesis. As part of the current project the Ecologic array was loaned to SAMS and was deployed from the HWDT research vessel Silurian. A variety of recordings of real porpoises in still waters and high tidal current areas were made and trials with test sound sources at known ranges and depths were undertaken. On the current project there was insufficient time to make definitive measurements of porpoise behaviour, however, it has served as a trial and proof of concept as well as providing the first indications of porpoise underwater behaviour in strong tidal current areas off the West Coast of Scotland.

Methods: Equipment

The vertical array comprised 4 individual hydrophone elements. These were configured as two pairs spaced 25cm apart with each pair separated by ~15m, see Figure 1. Each hydrophone pair was mounted in an oil-filled rigid plastic tube with a lead weight at the bottom which in turn was suspended within a free-flooding polythene cylinder. In this way, the hydrophone pairs were protected from the influence of water flow and were able to maintain a vertical orientation. Digital inclinometers attached to the suspension line just above the bottom cylinder and near the line’s attachment point on the boat above water, provided information on the orientation of the cable away from the vertical. The hydrophones in the array were Magrec HP03 units which each consisted of a spherical ceramic hydrophone and a 29dB preamplifier with an integrated 2kHz high pass filter. Signals from the array were processed using Magrec HP27 ST preamplifiers to provide additional gain and a 20kHz high pass filter was applied to the amplifier output. Signals were digitised at 500kHz using two synchronised National Instruments 6251 USB DAQ devices. Software to achieve this synchronisation was written by Douglas Gillespie and implemented in the PAMGUARD acoustic monitoring program.

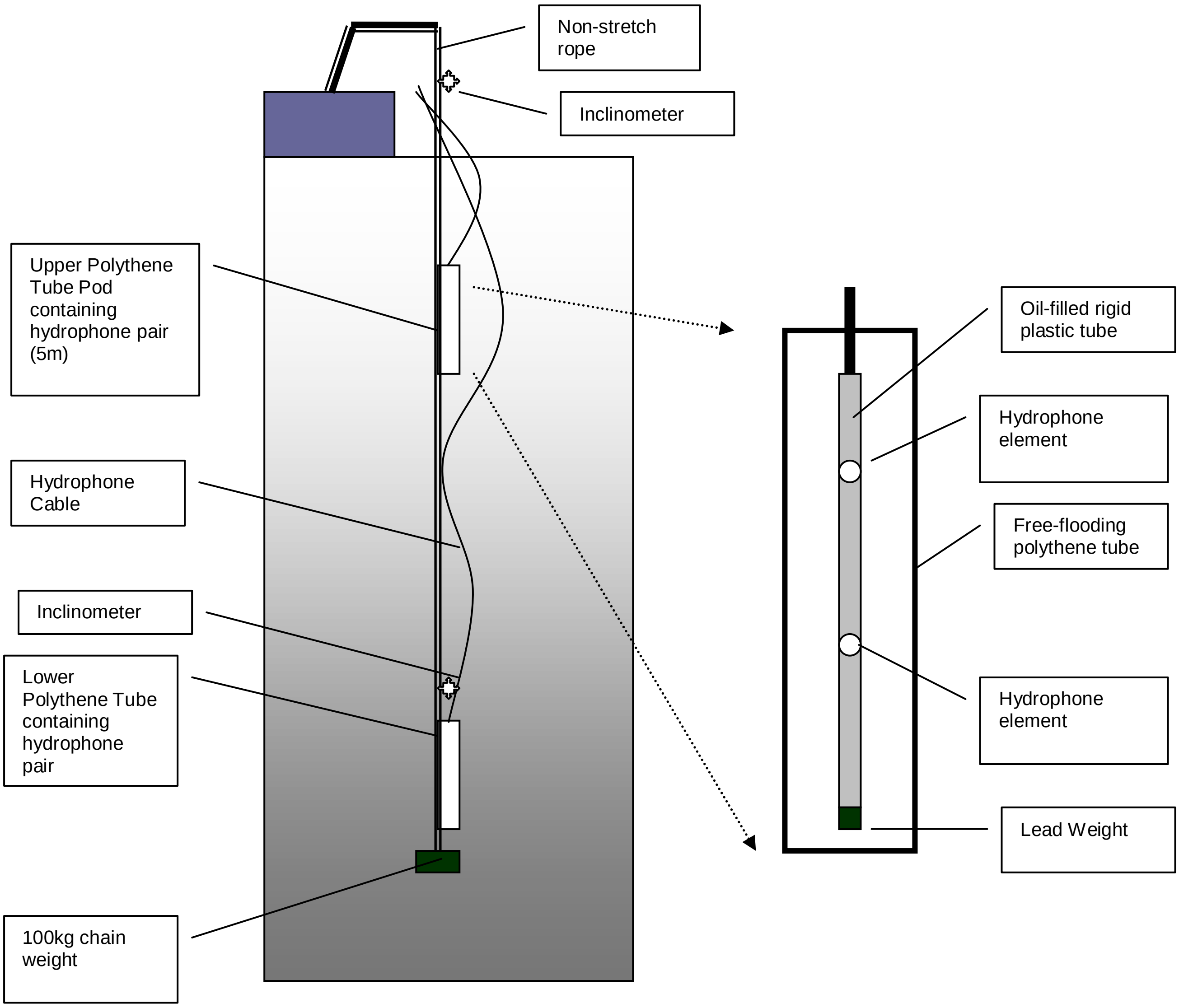


Figure 1. Four element vertical hydrophone array used for determining depth of porpoise vocalisations.

Data Analysis

Raw sound files were first analysed using click detector routines in PAMGUARD which was configured with each pair of hydrophones were treated as a paired channel. The click detector parameters applied were based on those typically used for detecting and classifying harbour porpoise clicks. The waveforms of these clicks, along with timestamps and information on the sampling rate and soundcard settings were packaged into .clk files (the format used by Rainbow Click). The recorded wav files from each hydrophone were run through PAMGUARD to detect likely porpoise clicks and a specially written Java program was then used to identify probable corresponding clicks on different hydrophones and localise using the MCMC techniques discussed below. (See Gordon et al. 2011 for details of the program).

Markov Chain Monte Carlo Localisation Method- Theory

An array of four or more hydrophones can localise in three-dimensional space. In this case practical considerations related to the feasibility of maintaining a complex array configuration in strong tidal currents led us to the use of a simpler vertical array consisting of two hydrophone pairs. Although the required number of hydrophones for three-dimensional localisation was met by this, the linearity of the array results in degeneracy of position after localisation so that only range and depth information are provided. In the case of a click incident on a single pair of hydrophones, the only information that can be extracted is the bearing to the sound source (porpoise). This bearing is resolved in three-dimensional space as a cone of possible of locations. The porpoise can be located anywhere on the surface of this cone; and the length of the cone is unknown. When a second pair of hydrophones is introduced, a second cone results. The intersection of these two conical surfaces indicates the position of the porpoise. For a three-dimensional array of four hydrophones there are six possible cones and there will generally be only one crossing point, providing a three-dimensional point localisation. However, because of the symmetry of the vertical array the cones always cross each other in perfect alignment, resulting in a ring of possible locations centred on the array. (Figure 2). Therefore, if the linear array is vertical both depth and range are determined.

Time of arrival delays were calculated for each hydrophone using a combination of PAMGUARD and custom Java script (see above) and a Markov Chain Monte Carlo Algorithm was then utilised to localise each click. Markov Chain Monte Carlo is a statistical method widely used in physics and astronomy. Figure 2 shows multiple hydrophones represented by black dots in three-dimensional space. **r**(*i*) and **s** represent the vectors from the origin to hydrophone *i* and the source respectively. Considering distance=speed x time this leads to the equation

$$(r_x(i)-s_x)^2+(r_y(i)-s_y)^2+(r_z(i)-s_z)^2=c^2*T(i)^2$$

where *c* is the speed of sound, *T*(i) is the total time from the source to hydrophone *i* with $r_{x/y/z}$ and $s_{x/y/z}$ the Cartesian components of **r** and **s.** Rearranging this yields**.**

$$T(i)=\frac{((r_x(i)-s_x)^2+(r_y(i)-s_y)^2+(r_z(i)-s_z)^2)}{c^2}$$

This significance of this equation is that it allows calculation of the expected time delays between the hydrophone elements for a simulated source located anywhere in space.

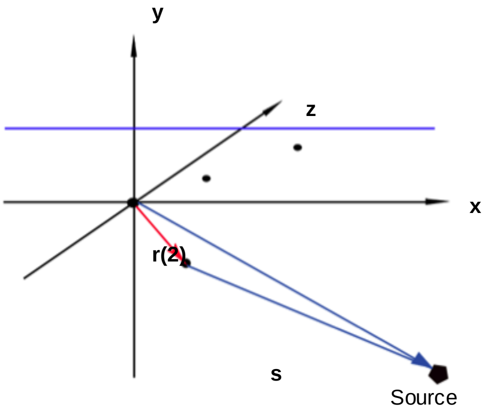


Figure 2. Vector diagram showing distance from source to hydrophone 2 in 3D space. Black dots represent hydrophones and hydrophone 1 is located at the origin.

Although straight forward this forms the basis of Markov Chain Monte Carlo localisation- from now on referred to as MCMC. MCMC localisation works by assuming a location in space and calculating the χ^2 of that location using.

$$\chi^2 = \sum \frac{(\tau_{obs}(ij) - \tau_{calc}(ij))^2}{\varepsilon^2}$$

where τ_{obs} *(ij)* is the actual observed time delay between hydrophones *i* and *j* and τ_{calc} *(ij)* is the calculated time delay between hydrophones *i* and *j* from an acoustic source if it was at the assumed location. ε represents the expected error in observed data. For a four hydrophone array i=1,1,1,2,2,3 and j=2,3,4,3,4,4.

If χ^2 is lower at the new location the jump is deemed successful and the new location is adopted. If χ^2 is not lower then the jump is only accepted as successful with a probability of

$$p = e^{-\left(\frac{\Delta\chi^2}{2}\right)}$$

where $\Delta\chi^2$ represents the difference in χ^2 values between the previous and new jump point. If still unsuccessful the new location is discarded and another random jump calculated from the previous location. If successful then a new random jump is instigated from the new location. In this way a chain of successful jumps results, converging quickly to the likely porpoise location. Once close to this location the chain then jumps around it creating a cloud of points, the density of which represents a probability distribution of the porpoise position.

The power of this technique is that it provides a reliable measure of the probability distribution for location and it can also easily incorporate other unknown parameters, in addition to the location of the porpoise. In the case of the vertical array for example, it is possible to allow the chain to search for unknowns in the position of the array.

Compensating for cable angle

Although inclinometers were included in the array they provided incomplete information on the array position. The inclinometer located on the top of the array was manually kept aligned with the bow of the survey vessel and thus provided exact information on the orientation of the top of the cable. However, due to the twist in the cable the orientation of the bottom inclinometer was not known and it therefore provided information on the angle of tilt but not its orientation. The orientation of the cable connecting both hydrophones is completely unknown. If one assumes inclination angles of Θ and azithumal angles of Φ (Figure 3) then there are three unknowns, Θ_2,Φ_2 and Φ_3. Plotting the inclination angles, Θ_1 and Θ_3 it is evident that a periodic variation in angle occurred.

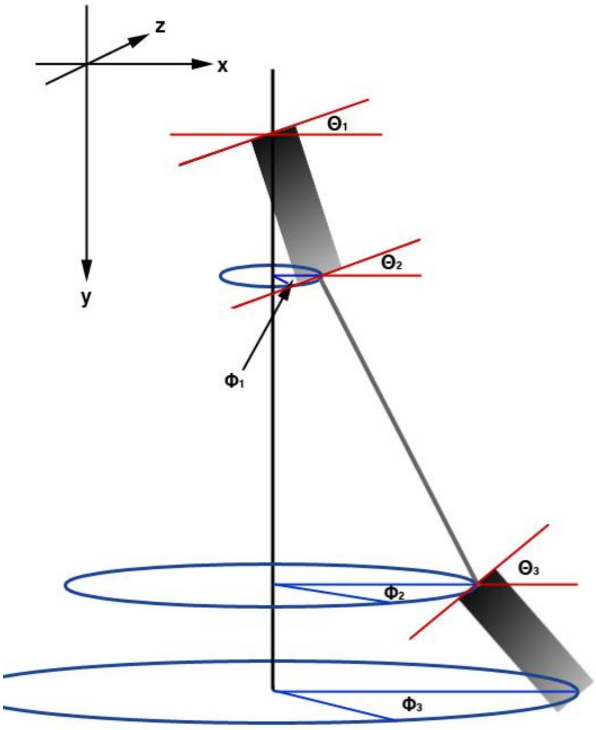


Figure 3. Diagram of the vertical array with an exaggerated offset angle. The shaded rectangles each represent a hydrophone pair. The red lines indicate the inclination angles Θ_1, Θ_2 ,Θ_3 and circles represent the resultant possible azimuthal components due to unknown direction and inclination of the cable. The co-ordinate axis represented the Cartesian co-ordinate system used throughout the project.

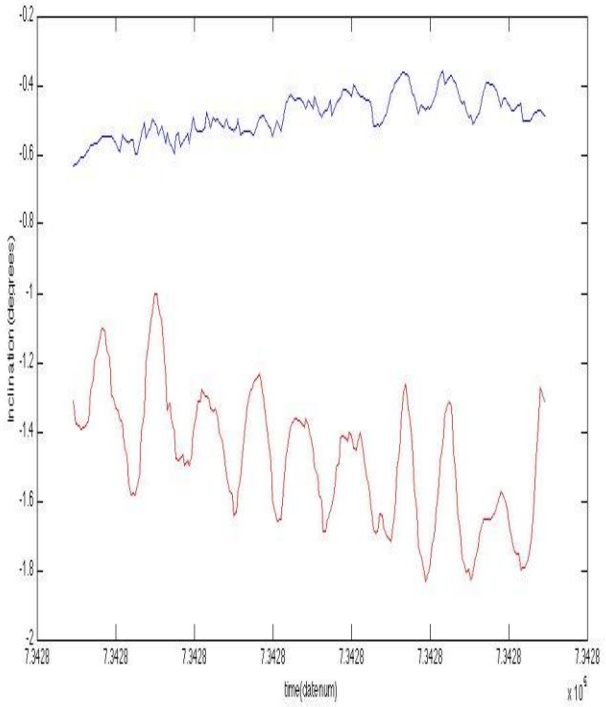


Figure 4. Inclination angles of the array over time May18 2010. Red represents to top inclinometer and blue represents the bottom inclinometer. Time is in matlab datenum format which converts date/time in a single number starting at 0 on Jan 0000 00:00:00 .

This periodic motion is attributed to the roll of the vessel and therefore it can be assumed that movement in the array is mostly in one plane. Thus the unknowns, Φ_1 and Φ_2, can be eliminated leaving Θ_2, the inclination of the cable, as the last unknown parameter. The Markov Chain therefore calculates a random position in space and a random value for Θ_2 on every jump.

Implementation

The method was implemented as a Java program. The test for a successful MCMC localisation is to determine whether several (in our case we used ten) different Markov chains all converge to the same probability distribution. The first 65% of each chain was discarded to remove effects from the initial starting locations and the mean and standard deviation of the depth and range of the remaining jumps calculated.

Final data was output to a spreadsheet showing time, depth and range along with errors for each localised click.

Field Calibration Trials

Methods

A porpoise click generator was used to broadcast simulated porpoise clicks to test the performance of the vertical array system. The click generator consisted of a 12V Sony XPLOD 1200W Car Audio Amplifier (XM-2200GTX) driving an HS150 hydrophone (Sonar Research & Development Ltd, Beverley, UK). The broadcast signal was a .wav file comprising a wave train of twenty simulated porpoise clicks created in MATLAB and this was output to a National Instruments 6251 DAQ card using a laptop computer. (We are grateful to Jay Barlow, NOAA Southwest Fisheries Centre, USA, for suggesting this playback equipment to us.)

The broadcast equipment was deployed from a drifting inflatable dinghy at a series of ranges of between 50 and 350m from the research vessel which was also drifting. At each range the transmission hydrophone was deployed at four different depths 2.5, 5, 7.5 and 10m. Range was measured using laser range finding binoculars accurate to 0.5m. The depth of the transmitting hydrophone was recorded using a UWATEC Aladdin prime dive computer accurate to 0.1m.

The vertical array was configured with hydrophones at water depths of 4.77, 5.13, 18.13 and 18.38 m and kept taut with a 100 kg weight.

Results

Although all broadcast click trains (out as far as 350m) were detected on a computer running PAMGUARD on the survey vessel, it was found that recordings that could be analysed to provide reliable range and depth measurements were collected at only five of these ranges. We suggest reasons for this below. Generally however, the results of the calibration are encouraging. Figure 5 summarises data for acoustically derived depth measurements. For transmission depth of 7.5m and deeper localizations were usually successful but, during this trial, depths were not calculated successfully for shallower transmissions. As Figure 6 indicates there is a good agreement in range measurements for distances out to 127m. At greater ranges, of 250 and 350m however, there were only sporadic detections from which a range could be calculated and these were not accurate.

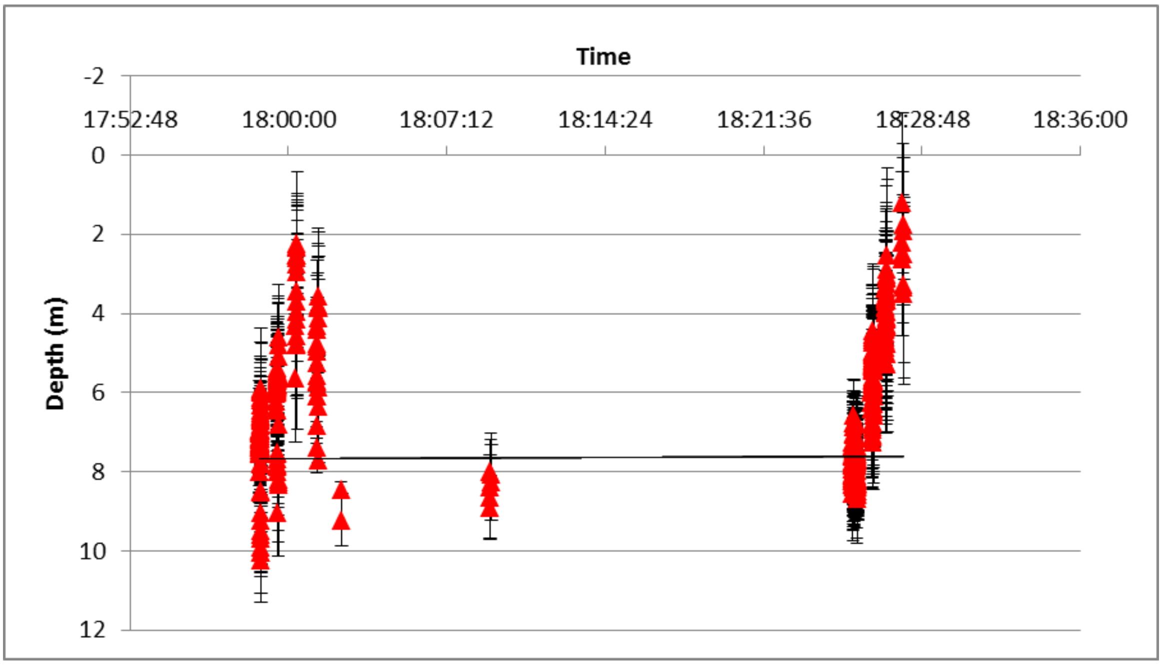


Figure 5. Depths calculated during calibration trials. Red triangles are the mean depth vale for all MCMC chains in each successful location. The error bars show the standard deviation of the MCMC probability density cloud.

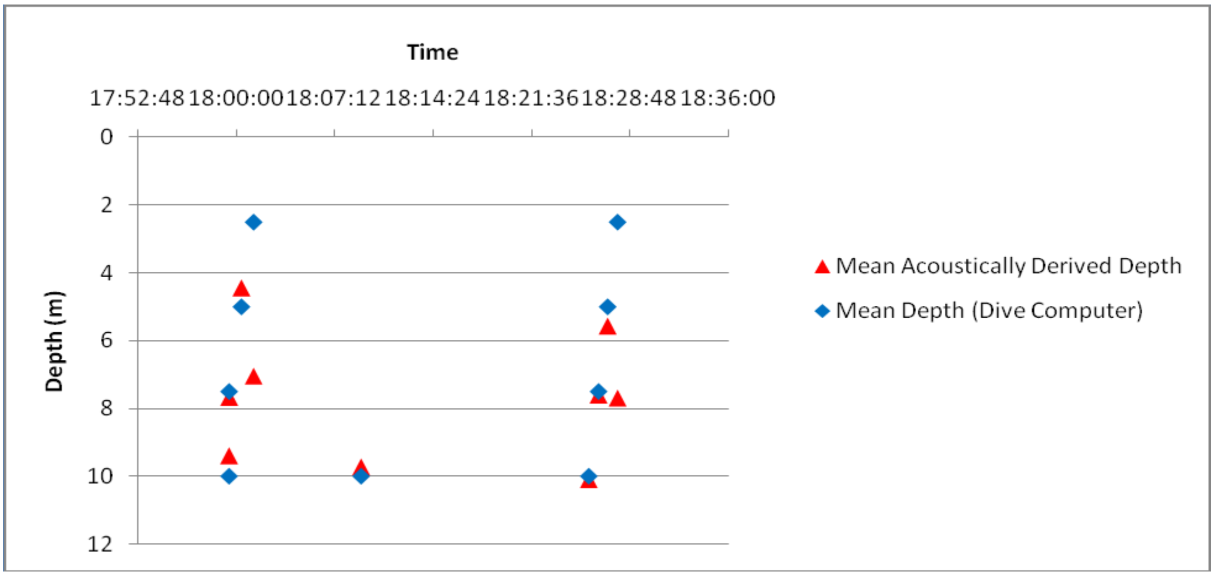


Figure 6. Depths calculated during calibration trials. Red triangles show the mean all calculated depths for each calibration station. The mean depth for the same station calculated using the dive computer data are show as blue diamonds.

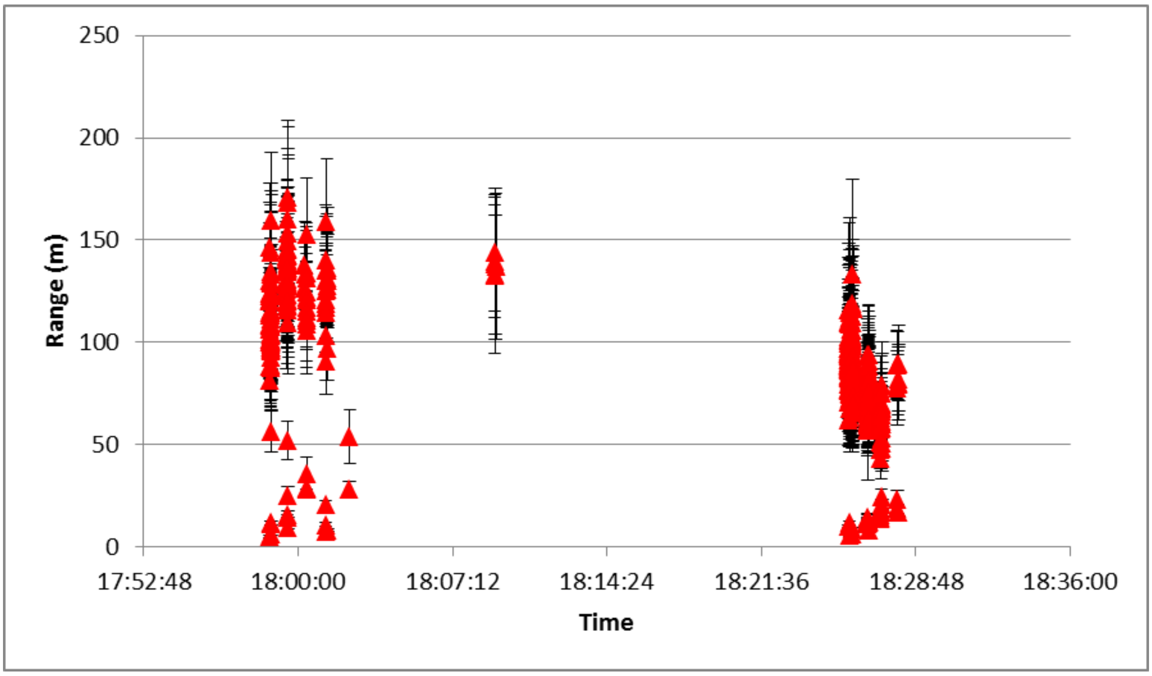


Figure 7. Depths calculated during calibration trials. Red triangles are the mean depth value for all MCMC chains in a successful localisation and error bars represent the standard deviation of the MCMC probability density cloud.

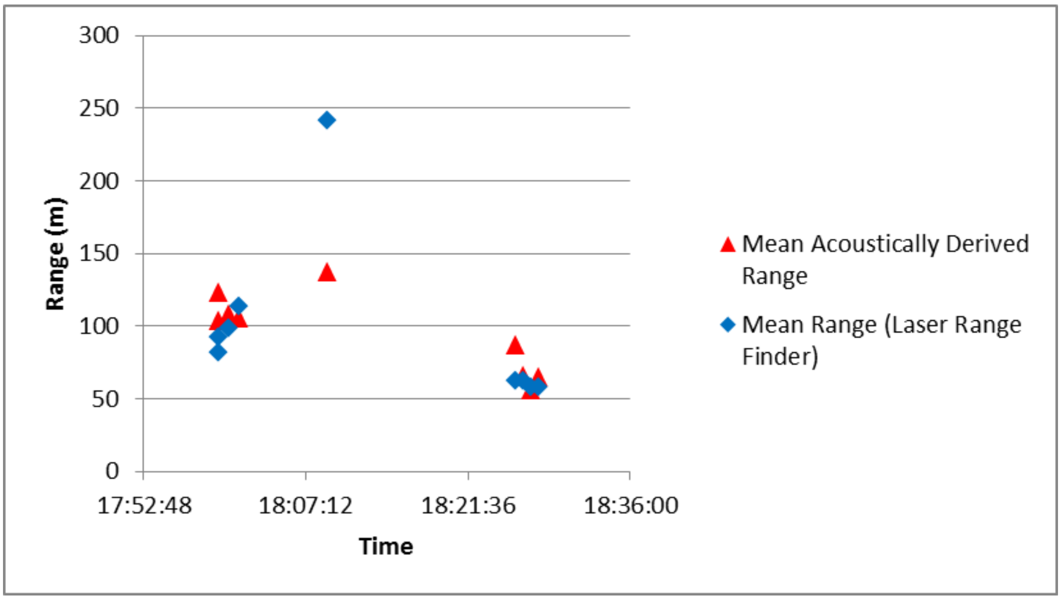


Figure 8. Range data from calibration trials. Red triangles are the mean range for all acoustic locations at a calibration station the mean of ranges measured using laser range finding binoculars as shown as blue diamonds.

Table 1 Ranges and depths of broadcast hydrophone during calibration trials

Time	Distance from Boat(m)	Depth of Hydrophone (m)
18:57:32	82	10
18:58:43	92	10
18:59:28	98	7.5
19:00:24	113	5
19:01:01	127	2.5
19:08:03	241	10
19:09:24	245	7.5
19:10:32	248	5
19:11:24	247	2.5
19:17:12	350	10
19:18:20	350	7.5
19:19:04	351	5
19:20:16	349	2.5
19:25:51	62	10
19:25:52	62	10
19:26:54	61	7.5
19:27:23	59	5
19:27:45	58	5
19:28:20	58	2.5

These trials indicate that within the range tested (7.5-10 m broadcast depth and 50-125 m), the method provided accurate results with good precision and no indications of bias. There are grounds for expecting that results at greater ranges might be better with real porpoise in typical field conditions.

Field Recordings of Porpoises and Dive Profiles

Extended recordings were made from the vessel drifting in still waters in Loch Duich on (15/05/2011 and 17/05/2011) and in tidal currents in the upper Sound of Sleat (18/05/2011). On both occasions porpoises were sighted in the recording locations though in the Sound of Sleat porpoises were often detected acoustically without being seen.

Figure 9 shows a histogram of all acoustically derived depths from vertical array recordings of harbour porpoise made during this project. This provides a first indication of the use animals make of the water column in these habitats.

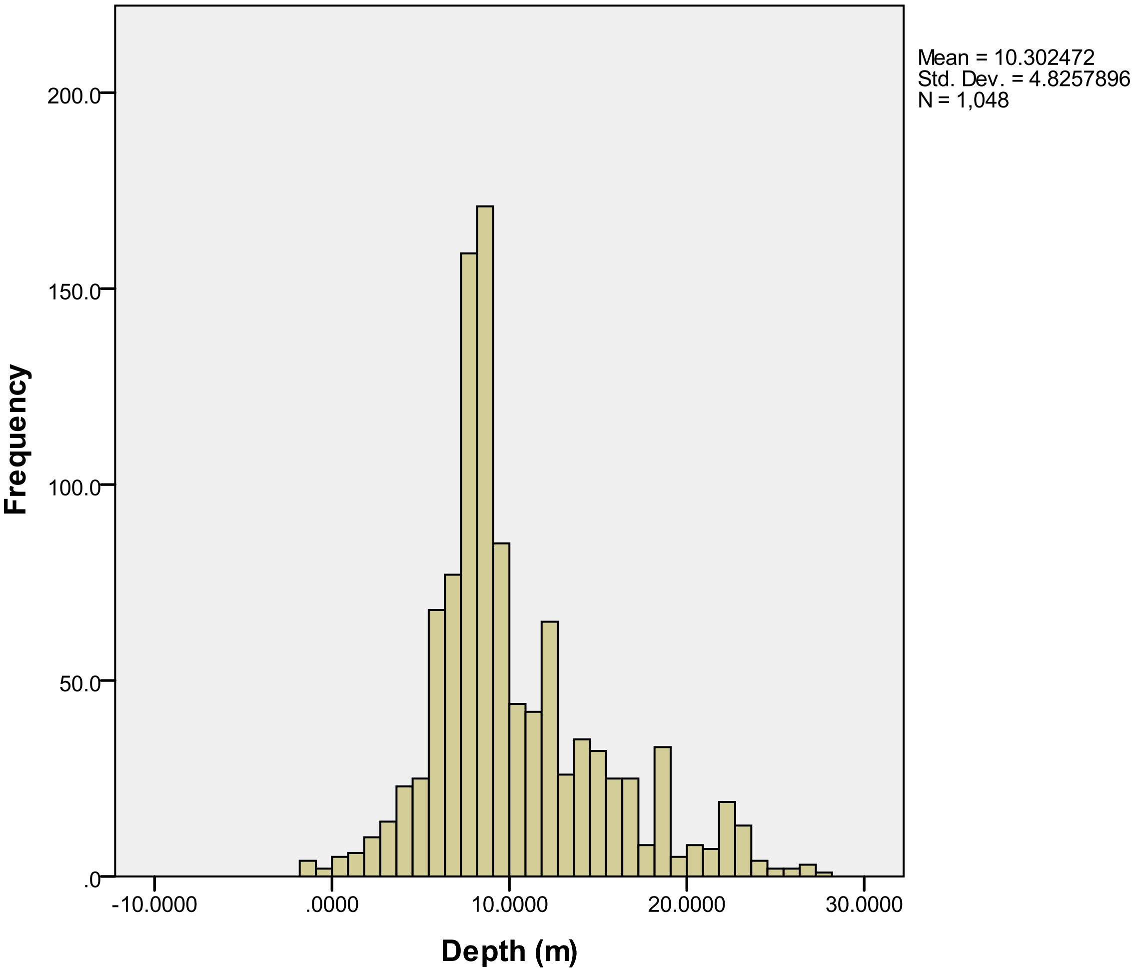


Figure 9. Histogram of acoustically derived depths for all acoustic encounters.

Figure 10 is an example fine-scale plot of range, depth and time. This shows a clear clustering demonstrating the correlation between all three variables - what is expected for dive profiles.

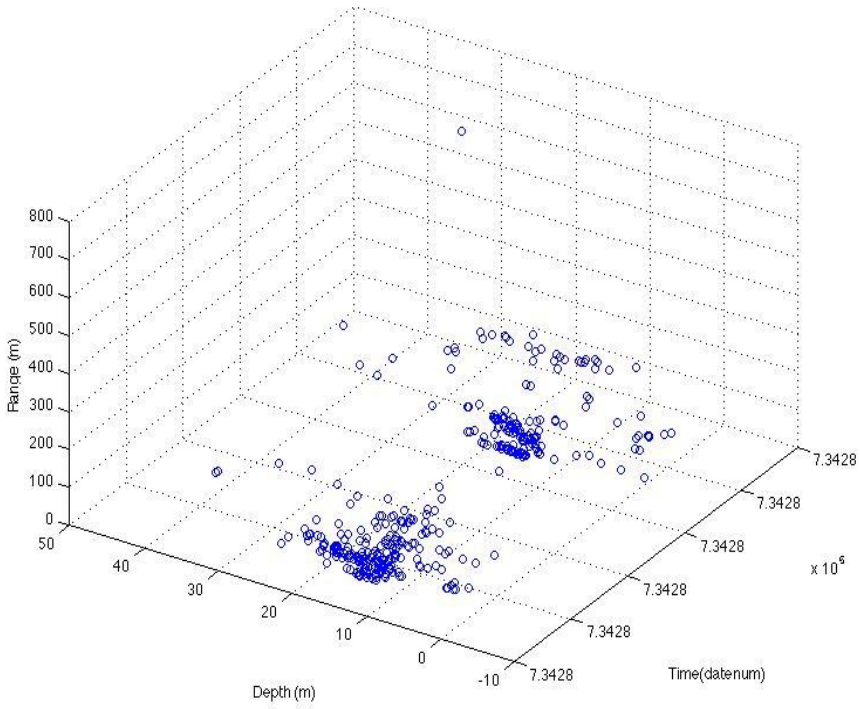


Figure 10. Example plot of Time v Depth v Range - May 18th. Note that time is in Matlab datenum format and depth and range are in meters.

Figures 11 and 12 show the locations of the research vessel, in Loch Duich and the Sound of Sleat respectively, at times when acoustic localisations were made in. Circles around these plots show them maximum range calculated during each sequence of locations. Although, as explained above, the location of porpoises cannot be calculated with a vertical array, it is likely that they were within these circles. A series of detailed plots of depth calculated using MCMC method against time which provide indications of dive profiles for individual dives are shown in Figure 13. These appear to show dives with durations of around 90-120 seconds and with dive depths of between 5 and 15 m. (The time on these plots can be cross referenced with the times shown next to locations in Figures 11 and 12 to determine the position of the boat during particular sequences.)

Clearly, depths can only be calculated when an animal vocalises, so these profiles will inevitably be patchy and incomplete. Here we have plotted profiles by simply linking calculated depths. An alternative approach would be to fit a line to these points statistically. These plots largely serve to demonstrate the future potential of the method to provide detailed information on underwater behaviour in area with high tidal currents which is highly relevant to quantifying collision risk. It is interesting to note that in these data porpoise are rarely, if ever, diving to the bottom as has been reported in other studies. If this is typical of their behaviour in these habitats then the risk of collision with turbines sited deep in the water column would be reduced. However, we emphasise that a larger effort will be needed in the future to provide reliable and representative biological information.

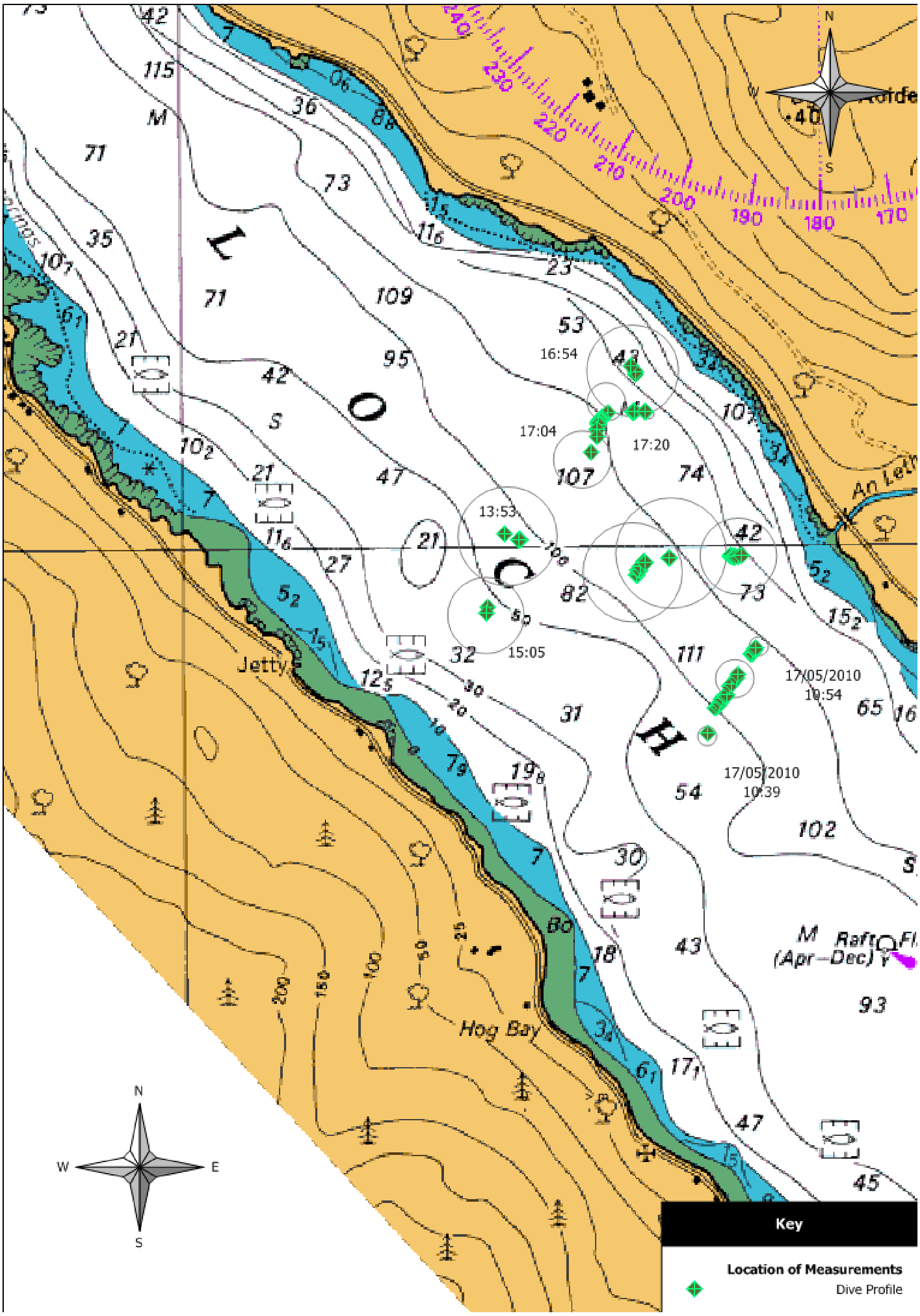


Figure 11. Locations and times at which porpoise acoustic depth data were calculated from vertical array recordings in Loch Duich on 15th and 17th of May 2010. (Dates are shown only for the 17th of May locations, which are furthest east.) Circles are indicative of maximum range for each location.

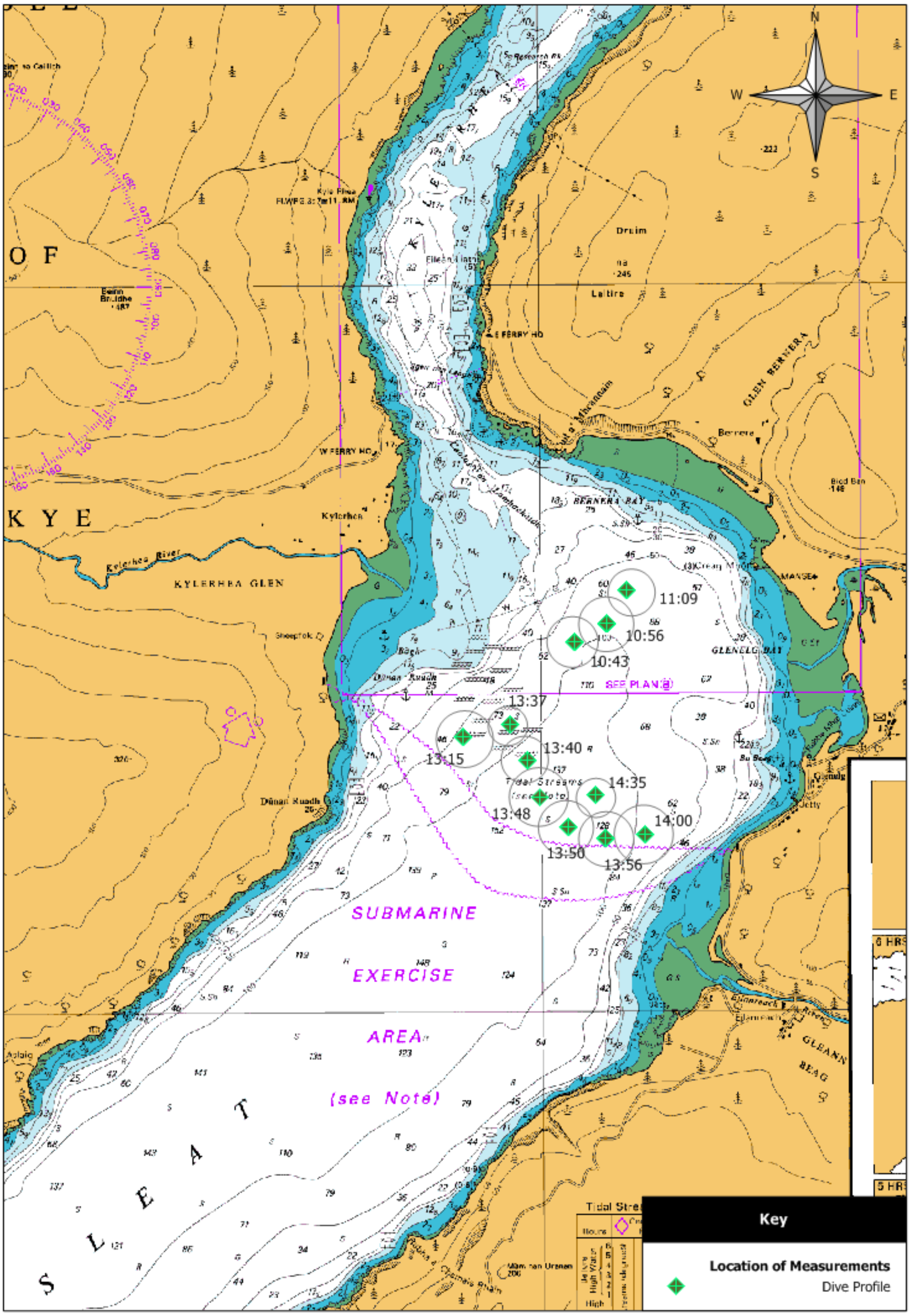
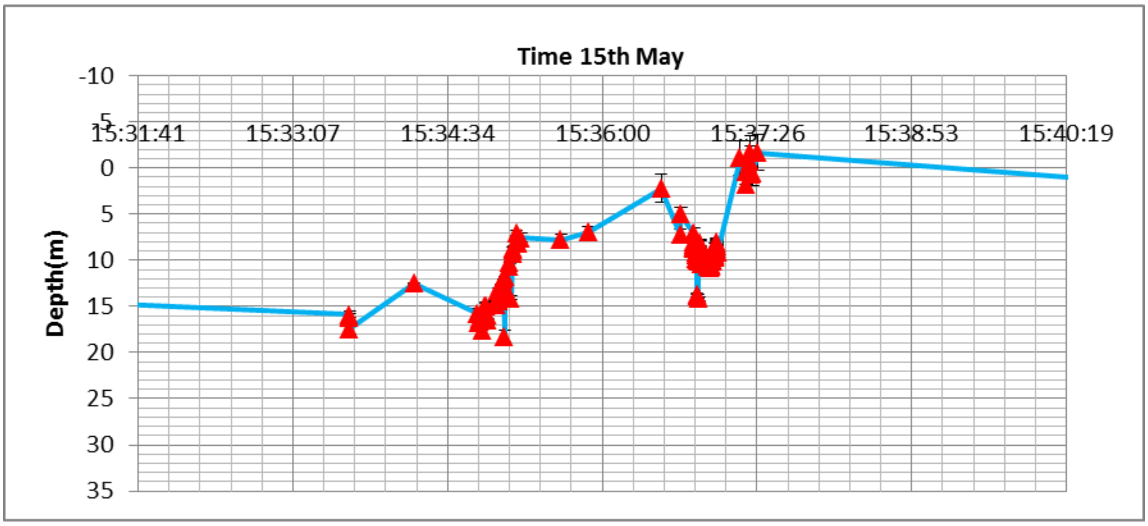
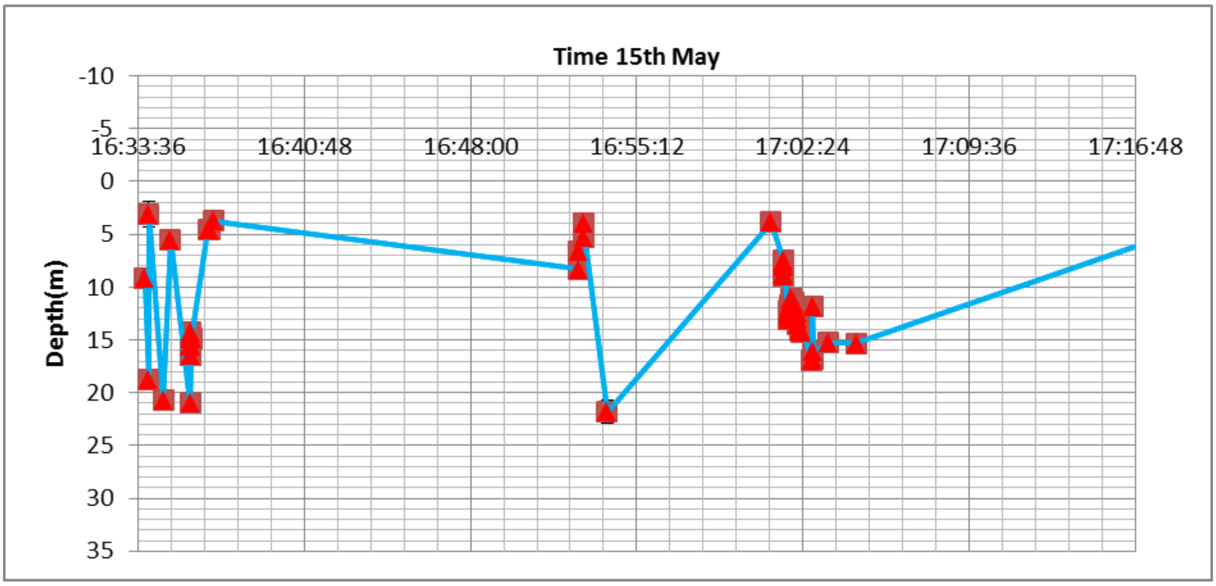
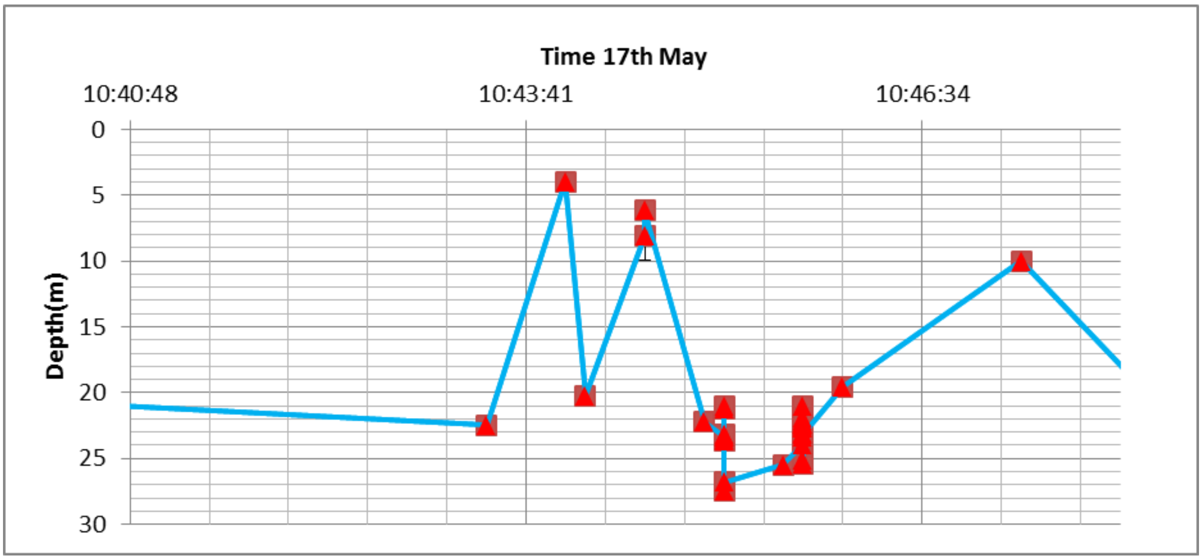


Figure 12 Locations and times at which porpoise acoustic depth data were calculated from vertical array recordings in the upper Sound of Sleat south of Kyle Rhea on the 18th of May 2010.


Time 15th May
-10
-5
0
5
10
15
20
25
30
35
Depth(m)
15:31:41
15:33:07
15:34:34
15:36:00
15:37:26
15:38:53
15:40:19


Time 15th May
-10
-5
0
5
10
15
20
25
30
35
Depth(m)
16:33:36
16:40:48
16:48:00
16:55:12
17:02:24
17:09:36
17:16:48


Time 17th May
10:40:48
10:43:41
10:46:34
0
5
10
15
20
25
30
Depth(m)

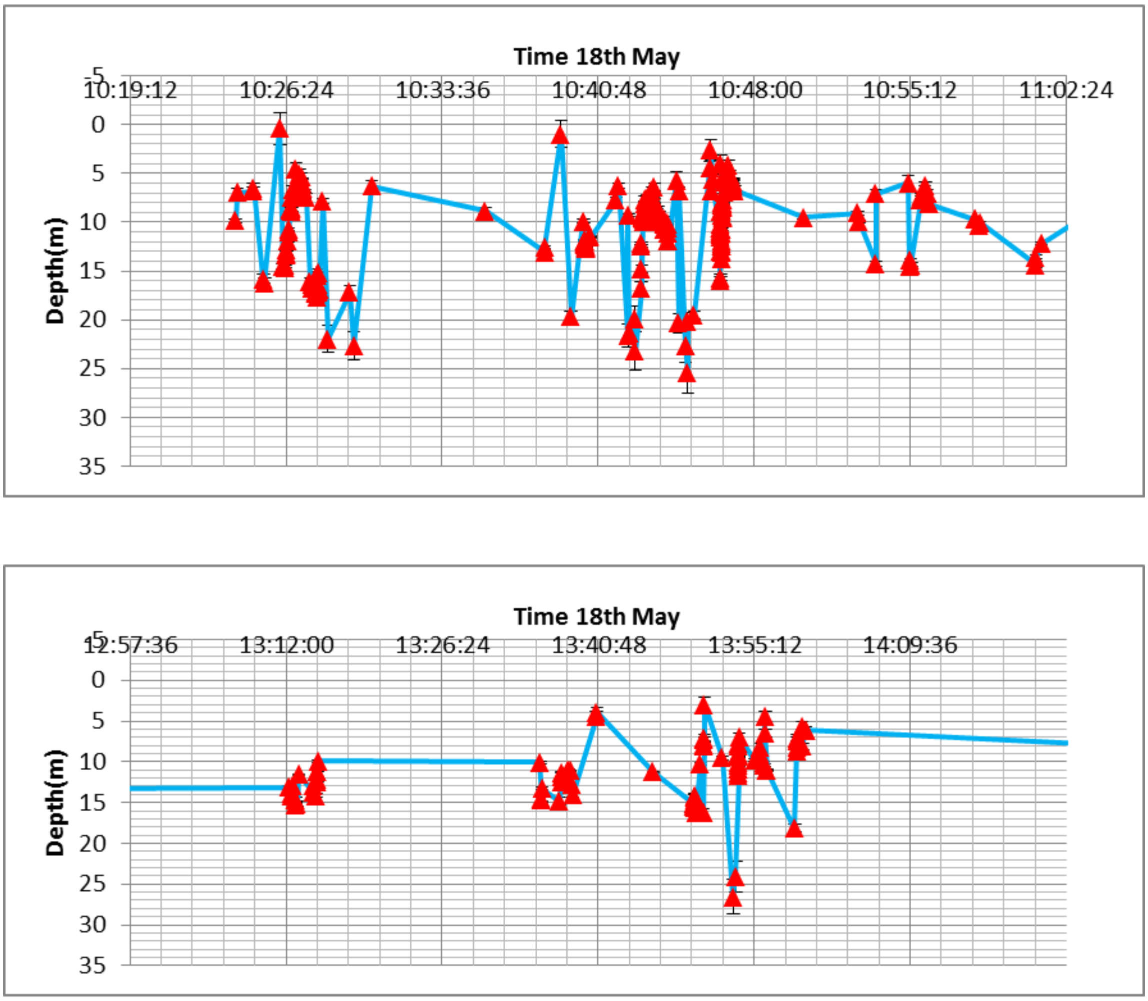


Figure 13. Plots of acoustically derived depth vs time giving an indication of dive profiles

Reference

Gordon, J., D. Thompson, R. Leaper, C. Pierpoint, S. Calderan, J. Macaulay, and T. Gordon. 2011. Studies of marine mammals in Welsh high tidal waters. N. Simpson, editor. Welsh Assembly Government. 152pp.

Appendix 2: Additional results from subsequent use of Drifting PODs

The promising results from the initial *Drifting POD* tests in May 2010 (Figs App 3.1a,b) prompted us to return to Kyle Rhea in August 2011 for another trial (Figs App 3.1c,d).

The results of this work:

1) confirmed the findings from the initial test – that the method provides rapid perspectives on porpoise distribution in moving water.
2) confirmed the findings of the more exhaustive visual and acoustic surveys using the *Silurian* that porpoises are not abundant in the tidal narrows but occur at relatively higher densities in the deeper waters to the south.

Please note that the data collected in the 2011 trial were not part of this hot-spots project (funding from elsewhere) but are included here as they add to and strengthen the general findings from the other techniques outlined above.

Figure App 3.1a

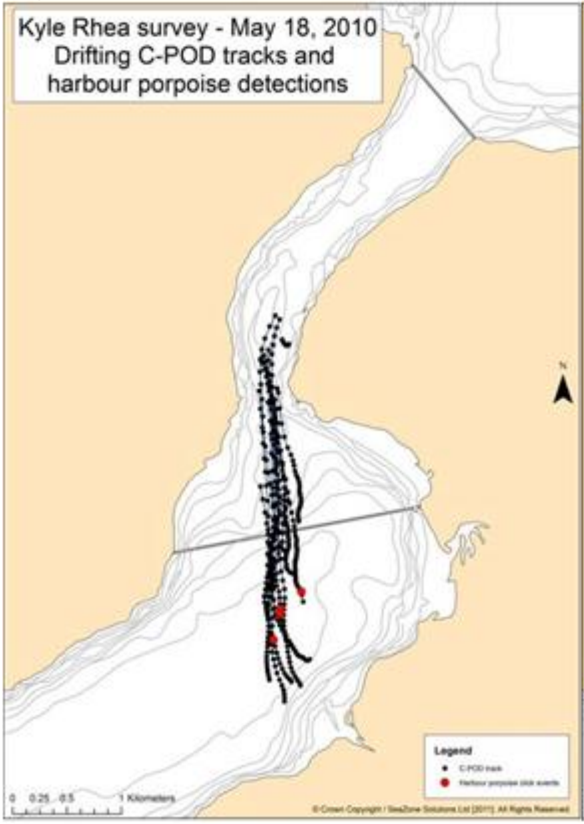


Figure App 3.1b

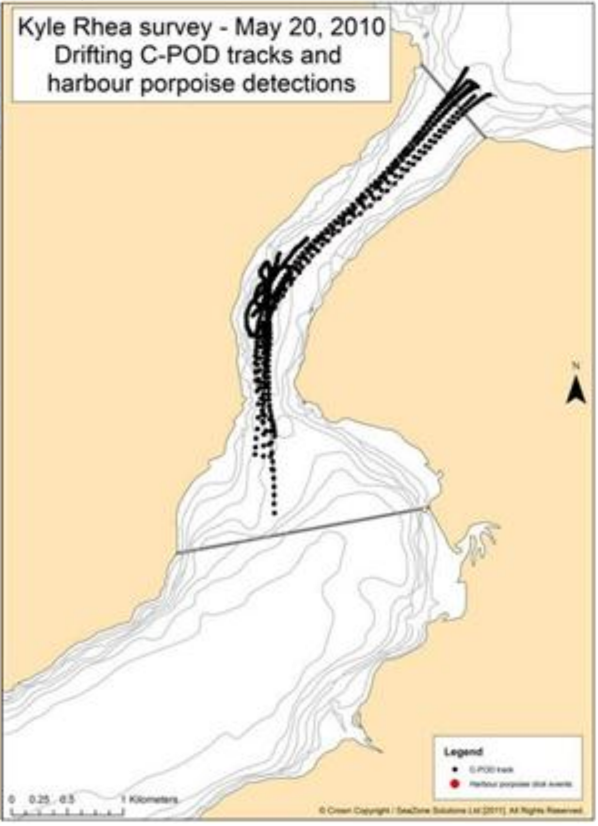


Figure App 3.1c

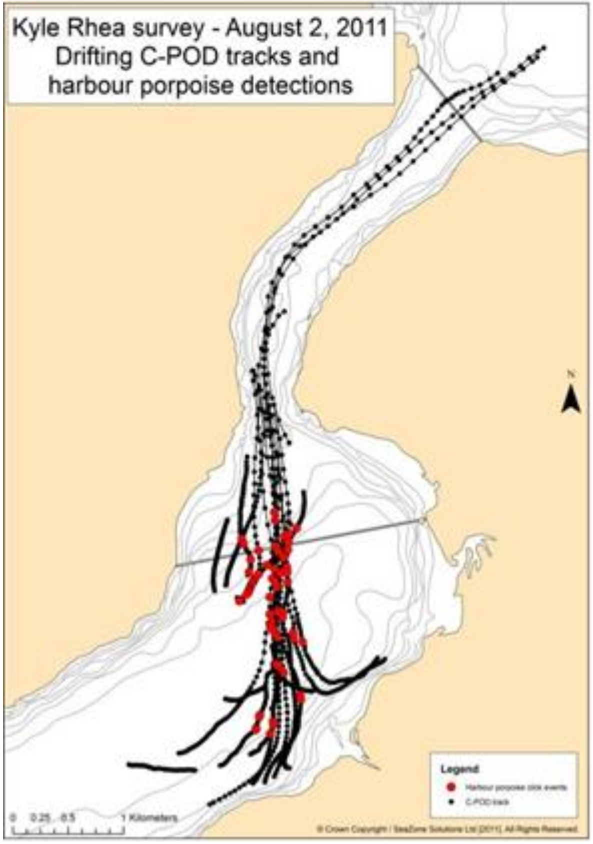
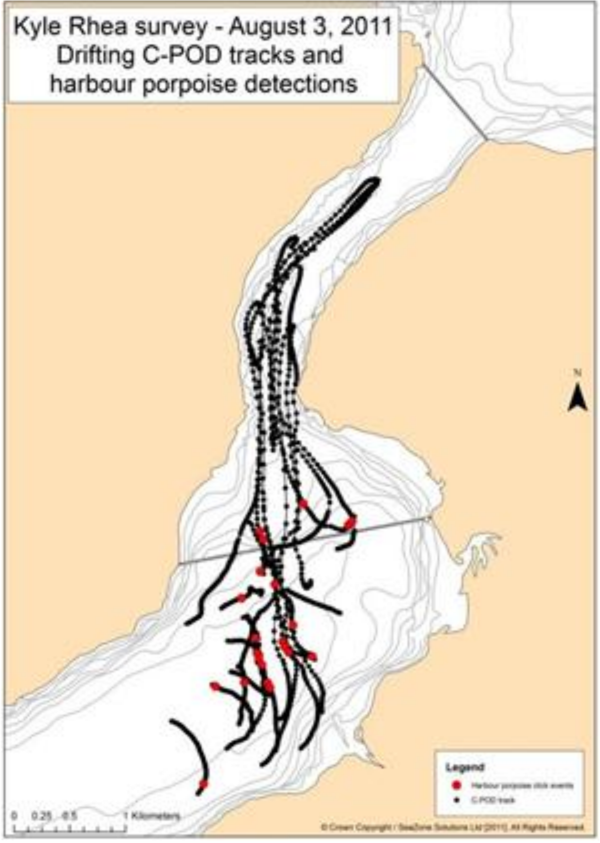


Figure App 3.1d



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